Linkage Synthesis and Optimisation Techniques with Skiboard Product Design Case Study

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Abstract

This thesis explores the design development and experimental testing of a planar linkage for the Skiboard, a novel snowsports equipment device. The Skiboard, similar to a skateboard in appearance and style of use, combines two short skis with a bindingless board. Its aim is to fill a gap in the snowsports market for a product that offers a wide range of freestyle and trick riding possibilities, beyond those of a snowboard, while being as stable and easy to ride as a pair of skis.

While the concept of the Skiboard in itself is simple, the task of designing a mechanism to link the skis to the board is complex. To translate a gradual lean of the rider into a gradual and equal tilting of the skis requires a multi-loop linkage mechanism. The synthesis and analysis of a mechanism for this application was the inspiration for the development of the synthesis-related design tools presented in this thesis.

Design methodologies and design software concepts have been developed for use by designers faced with under-defined, "black-box" linkage synthesis problems similar to the Skiboard mechanism synthesis task. A software-based design of experiments setup, called SMAC, is introduced in this thesis and was used throughout the linkage synthesis process for the Skiboard. One promising candidate mechanism, developed and chosen using SMAC, is followed through to the pre-prototyping phase of the design process.

PSEO, another, more advanced, software tool for complex and multi-loop linkage synthesis is also presented in the concept stage of development. This type of program has the potential to automate some of the most time-consuming portions of the synthesis and analysis process with the use of a genetic algorithm and curve-matching algorithm. Additionally, it keeps much of the user's interaction with the design process and the design

itself intact, which is something not offered by existing tools incorporating similar levels of automation.

Overall, this thesis is an exploration into the field of linkage design, a topic with little crossover between theory and practical design helps. It includes a review of existing synthesis tools and the development of new tools to suit complex applications such as the Skiboard. The design process for the Skiboard linkage mechanism is also presented and illustrates the way in which the creative design process is iterative, progressively informing the designer's understanding of the functional requirements of the linkage and how to best satisfy them.

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A mon prof prefere, vous savez qui vous etes: To you, I owe a debt of gratitude.

To Ben, a rare and perfect blend of intelligence, heart and vibrant soul, thank you so much for your patience and constant support. Je suis heureuse etre ta femme.

I would like to dedicate this thesis to my ever loving, ever generous parents who are truly the world's best, and to my grandmother, Carolyn, who will never be forgotten. Thank you all for teaching me at a young age to finish what I start.

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Glossary

Closure Error: Occurs when a candidate mechanism cannot be assembled for all specified positions. This type of error manifests as a rebuild error in the SolidWorks parametric modelling environment.

Compound Mechanism: A mechanism that meets two or three functional requirements, usually created as an amalgam of two or more kinematic chains. This type of mechanism can be a multi-loop linkage, but – by this definition – does not necessarily contain more than one loop.

Conceptual Mechanism Design: The process of mechanism type synthesis and enough concurrent dimensional synthesis to ensure that the solution meets the functional requirements.

Constraints: All restrictions placed on a design; must be a function of at least one design variable. (Arora 2004)

Coupler: The link in a four-bar linkage that is not connected to the ground. Sometimes referred to as the output link.

Design Constraints: Limitations on the conditions under which a design is developed, or on the requirements of the design.

Design Degrees of Freedom: Number of independent variables for a problem.

Design Variables: System values that can be changed; all unknowns of an optimisation problem. (Arora 2004) In linkage design, the design variables are usually the dimensions of the links that are not of a fixed length.

Degrees of Freedom (DOF): Also called the mobility of a mechanism, it is the number of input parameters that must be controlled independently in order to bring the device into a particular position. (Uicker, Pennock et al. 2003)

Dimensional Synthesis: Sometimes referred to as **Dimensional Optimisation**, this part of the linkage design process involves finding optimal dimensions for links in a chosen linkage topology.

Factors: Controllable experimental variables that can influence the observed values of response variables.

Fitness Function: See **Objective Function**

Functional Requirements: Three types of coordinated link motion: path generation, motion generation and function generation. Linkages can be synthesised to fulfil one or more of these requirements.

Genetic Algorithm (GA): A type of heuristic search that mimics natural evolution to find an optimal solution.

Geometric Constraint Programming (GCP): A technique for synthesising planar linkages using the sketching mode of modern parametric design software. This interactive synthesis method employs graphical synthesis techniques and the capability of parametric design software to solve non-linear kinematic equations without the involvement of the designer on an analytical level. (Kinzel, Schmiedeler et al. 2006)

Higher Pair: Links that have link and point contact such as gear teeth, or a cam and follower. There are infinitely many examples of higher pairs. (Uicker, Pennock et al. 2003)

Kinematic Chain: A chain of links with mobility, without any fixed link.

Kinematic Structure: Symbolic representation of a linkage mechanism that contains the essential information about which link is connected to which other links by what types of joints. (Tsai 2001)

Kutzbach Criterion: Equation representing the degrees of freedom, or mobility, of a mechanism. $m = 3 (n - 1) – 2j_1 – j_2$

Linkage Configuration: A linkage with a particular combination of link dimensions.

Linkage Optimisation: The process of finding the most suitable set of dimensions for a linkage relative to an objective function or set of rules. (Da Lio, Cossalter et al. 2000)

Lower Pair: Links that have surface contact. There are six types of lower pairs: Revolute, prismatic, screw, cylindrical, spherical and planar. (Hartenberg and Denavit 1964)

Mechanism: An “assemblage of resistant bodies, connected by moveable joints, to form a closed kinematic chain with one link fixed and having the purpose of transforming the motion.” (Uicker, Pennock et al. 2003) For the Skiboard mechanism, the ground is considered the fixed link.

Mechanism Synthesis: The process of "prescribing the sizes, shapes, material compositions and arrangements of parts so that the resulting machine will perform the prescribed task." (Uicker, Pennock et al. 2003)

Multi-Loop Mechanism: A linkage, usually comprised of six or more links, that is described using more than one closed-loop position equation. Linkages with more than six links are always multi-loop in nature. (Doughty 1988)

Objective Function: A scalar function used to compare different designs. (Arora 2004)

Parametric Sketching and Evolutionary Optimisation (PSEO): Early-stage complex linkage synthesis tool incorporating 2D parametric sketching and automated experimental synthesis and optimisation. PSEO is presented as an original concept in Chapter 4.

Penalty Function: Also called a cost function. An objective function that is to be minimised during the optimisation process. (Arora 2004)

Planar Linkage: "Planar mechanisms utilizing only lower pairs" (revolute and prismatic joints). (Uicker, Pennock et al. 2003)

Product Development Methodology (PDM): The sequence of steps or activities which a product design team (or person) employs to conceive, design, manufacture, and, commercialize a product.

Product Design Specifications (PDS): "The precise description of what the product has to do." (Ulrich 2003) Each specification consists of a metric and a value. Product specifications can be defined and organized according to many different product design methodologies. Baxter (1999) proposed the structure adopted for the design task in this thesis.

Singularity: A position or configuration of a mechanism that results in the forces or other physical quantities involved being infinite or nondeterministic.

Solid Model Atlas Creation (SMAC): Early-stage complex experimental linkage synthesis tool designed for the development of the Skiboard. This tool is presented and explained in Chapter 3.

Introduction

This thesis presents the design and development of a linkage mechanism for a novel snowsports equipment device, called the Skiboard. The Skiboard is a recreational device meant for freestyle and downhill riding in snow. It is meant to give the rider a binding-free riding experience that is more flexible and stylistic than either skiing or snowboarding. The device itself is comprised of two short skis and a deck, linked together by a linkage mechanism. The design and optimisation of this mechanism, as well as research on the topic of mechanism design, is detailed in the chapters to follow.

The design and development of candidate linkage mechanisms for the Skiboard took place in an iterative fashion, as is the case with most complex mechanical design problems. As a result, a gradual refinement of the design specifications occurred. This resulted in the establishment of a better-constrained design problem and a progression of solutions that has moved towards satisfying the design specifications.

In the course of designing the Skiboard, a review of literature relevant to the linkage synthesis process was conducted. As the existing literature in this field is vast, varied and, some of it, very technical in nature, the findings of the literature review are presented as a possible help to future mechanism designers. The presentation of the findings includes a basic evaluation of the strengths and weaknesses of existing synthesis techniques, specifically with respect to loosely defined, under-constrained design problems like the Skiboard.

As part of this research, new synthesis techniques were developed to assist with the solution of the Skiboard linkage design process. The first, called Systematic Mechanism Atlas Creation (SMAC), allows the designer to create a 3D virtual model of a proposed linkage solution and set up an automated experimentation environment to test dimensional combinations in search of optimal solutions. The program traces the path of specified output link(s) and compiles these results into an atlas.

The mechanism designer can use atlases generated by SMAC to find potential solutions or to inform the next design iteration by producing a new linkage configuration. Formal experimental design analysis methods can also be integrated into the program to assist in determining the sensitivity of the link dimensions, or which of the variables most significantly influences the output behaviour. SMAC is the first formalised linkage synthesis/optimisation method of its type.

A concept for a more advanced experimental synthesis method was developed to satisfy some of the limitations of the SMAC program, called Parametric Sketch Experimental Optimisation (PESO). PSEO relies on the simplicity of a 2D parametric sketch of a linkage to perform complex dimension optimisation calculations. Unlike SMAC, PSEO offers the advantage of not only creating an experimentally-developed atlas for a linkage, but of assessing each configuration's suitability as an optimal solution and proposing one "most optimal" solution at the end of an experimental run.

The highly automated nature of the PSEO concept requires the use of a genetic algorithm package to automatically search the design space for solutions. It also requires a curve matching (or object recognition) algorithm to compare the results of each virtual experiment to the desired results. As the development of these tools will require further research, it is recommended as an area of future work, especially in light of the fact that experimental mechanism synthesis has been identified by authors in the field as the way forward (Mruthyunjaya 2003; Reifschneider 2005).

In light of the importance of validation of software tools, the “best concept” solution for the Skiboard mechanism was tested with the COSMOSMotion force analysis package. The effectiveness of SMAC in predicting the motion-related behaviour was validated. The “best concept” solution was designed for early-stage prototype manufacture, to be completed in a future phase of development.

The outcomes of this research, with regard to the Skiboard, include refinement of the product design specifications and significant advancement towards a solution linkage. Additional outcomes include the SMAC and PSEO concepts, which offer experimental synthesis tools for practical application by designers faced with complex tasks. In particular, the PSEO concept presents the opportunity for future development.

Chapter 1.

New Skiboard Concept Development

The Skiboard is a new product that blends the freestyling benefits of a snowboard with the stability and manoeuvrability of a pair of short skis. The equipment itself is made up of a pair of short skis, linked to a bindingless board by a novel linkage mechanism that controls the relative motion of these three elements. The design of this complex mechanism, and its inspiration for further research related to the mechanism synthesis and optimisation process, is the topic of this thesis.

The purpose of this chapter is to familiarise the reader with the Skiboard design task, the associated product design specifications and the structure of the thesis. The introductory portion of this chapter presents background relevant to the snowsports equipment industry and the Skiboard's place in the existing market. It is followed by a description of the anticipated outcomes for this research and a review of the mechanical design methodology used in the Skiboard design process.

1.1 Project Context

Modern snowsports have advanced greatly in variety and popularity over the last 50 years with the innovation of the modern alpine ski and the advent of the snowboard. In 2008, 1.4 million people in the United States alone participated in some type of snowsports activity. This data, collected by the National Sporting Goods Association in 2008, reflects the number of participants involved in alpine skiing, snowboarding and cross-country skiing. Freestyle snowsports participants using lesser known or homemade equipment were not accounted for in this study. Thus, the number of snowsports participants in the market for equipment is even larger than the data suggests.

Snowboarding, in particular, has become intensely popular among teenagers and young adults with an interest in freestyle riding. Freestyle riding is defined as trick and style-based riding involving air-borne manoeuvres and traversing of off-piste terrain. According to U.S. market statistics, snowboarding is more popular than skiing among snowsports participants younger than 35. The snowboard continues to rise in popularity due to the fact that it affords a great range of upper body movement and enables extreme sports enthusiasts to perform jumps and tricks on the snow.

While it does offer creative riders a perceived and physical advantage over skiers, snowboarding still has limitations. These limitations are most readily experienced in snow parks, where the ability to dismount, easily carry the board and flip the board under the feet are not afforded by snowboards due to the bindings. A gap is thus left in the market for the development of new types of winter sports equipment.

As compared to products like the skateboard, the snowboard does not allow for the range of lower body movement or artistic freedom desired by many freestyle riders. Snowboard bindings prevent foot and ankle movement, which severely limits the range of possible body positions. In addition, the boots and bindings must both be purchased separately and carefully sized, which usually restricts the usage of a set of snowboarding equipment to just one person. In contrast, skateboards are relatively interchangeable, making them economic casual-use recreation equipment.

Since snowsport equipment can generally only be used for one season out of the year, the expense of buying skis, boards and bindings is a deterrent to equipment ownership. Thus, economics drive this problem and the search for an inexpensive, more universal and interchangeable product with which to enjoy winter sport.

Riding a snowboard can also be a tricky skill to master, especially for those with no previous skiing or skateboarding experience. Turning requires coordination, concentration and experience, as turns are carved with the weight of the rider balanced on one edge. Falls while snowboarding can be particularly painful and prone to resulting in injury. The rider's feet are not released from the bindings automatically in event of a crash, as with skis, so the rider must use his or her hands and arms to break a fall.

A hard fall from a snowboard often results in wrist or head injury. Approximately 25% of all snowboarders who injure their wrists end up with fractures, compared to 12.5% of skiers. (Langran) Head injuries occur less frequently, but still constitute 10 to 20 percent of all injuries on the slopes. (Langran)

A skateboard-type apparatus can be easily dismounted if desired or necessary, meaning the rider can more easily pre-empt a fall than while riding a snowboard. With the legs free, impact is less likely to be absorbed by just the upper body. For these reasons, a skateboard-like product would fill a gap in the market for a safer alternative.

1.1.1 New Product Concept

The aim of this research is to develop and analyse the mechanics of a product that has been designed to fill the existing gap in the snowsports market. This product, called a Skiboard, is a skateboard-style apparatus that blends the benefits of skiing and snowboarding. The Skiboard allows snowsports enthusiasts to explore a broader range of trick riding possibilities. It also offers an alternative to skiing or snowboarding for those who wish to participate in a winter sport that is fun and easy to learn with less risk of wrist or head injury in the event of a fall. The Skiboard creates safer riding conditions on the snow field because the rider will be free to dismount the board at will, thus having the ability to avoid imminent falls by jumping off the board or to use the feet to stabilise if a fall does occur. Hence, a market and recreation niche exists if the right design can be found to bring the Skiboard concept to fruition.

Others have produced products with characteristics similar to the Skiboard. However, none have managed to develop equipment that offers the rider the freedom to perform skate-park-style tricks in an uninhibited (untethered) stance while providing enough stability and control to safely ride downhill at speed. The Burton Snowdeck, for example, joins a single ski to a board, as shown in Figure 1. The Premier Snowskate, also shown in Figure 1, is a stand-alone board deck designed for trick riding. These products offer versatility of movement, but both are difficult to ride and ill-suited to downhill runs.

An additional similar product, the Railz Snowskate, is comprised of four small skis that are mounted to a deck via skateboard trucks. The disadvantage in this design is that the movements of the front and back skis are not coordinated. In turns the skis chatter due to misalignment, which poses problems for the rider when manoeuvring. The Railz Snowskate is also shown in Figure 1.

The Skiboard concept is comprised of a bindingless board mounted on short skis by a linkage-type mechanism. The aim is for the rider to stand on the board as he or she would on a skateboard and control its movement by leaning laterally forward or backward. As the Skiboard has no bindings, the rider is able to push the board along the snow with the back foot or dismount if a fall is imminent, making this equipment well-suited for both snow park and alpine environments. The top of the board is fitted with a rubber, self-cleaning high-friction grip pad to prevent slipping. The board rests on two bi-directional short skis, which contact the snow and give the rider stability and control in turns.

Burton Snowdeck

Premier Snowskate

Railz Snowskate

Figure 1: Competitor Products

The experience of riding the Skiboard is more similar to riding a skateboard than skiing or snowboarding. Thus, the range of stunts that can be performed during a ride on a skateboard is similar to those allowed by the Skiboard. While the mechanics of the skateboard riding experience were used as inspiration for the design of this product, the construction and mechanisms comprising a skateboard do not lend themselves to being translated to riding on snow.

The trucks used to turn skateboard wheels in response to a lean by the rider tilt the wheels towards each other to create a turning circle. These trucks cannot by applied to the Skiboard because it is comprised of two skis that extend the length of the board. It is not necessary to bend the skis into the shape of the turning circle via a mechanism because the side cut of the skis already provides this circle.

The mechanism connecting the board to the skis is the enabling component compared to prior efforts. This component gives the product its uniqueness and value in the marketplace. Its design was the inspiration for this research.

While the concept of mounting a board to a pair of skis is not a novel idea in itself, a mechanism that attaches the two components and creates a smooth, easily-controlled ride without the assistance of springs is a new technology. It is different from other efforts in this area of design (as compared to patents filed by Lefebvre-Dexpeaux and Barbieri & Cappozzi) because it provides a deck for the rider to comfortably stand on and two skis in contact with the snow for stability and turn carving. Additionally, in contrast to a device patented by Lion in 1996, it contains a mechanism that keeps the tilt of the skis equal to avoid chatter.

The Skiboard design aims to fulfil the following specifications and associated sub-specifications:

- Carve smooth turns in groomed snow so that it can be taken and enjoyed on the same type of terrain as skis and snowboards.
- Provide the rider a feeling of gradual resistance as his or her weight shifts toward the lateral edges of the board. It is important for the rider to have a sense of control and balance while on downhill runs.
- Maintain a stable horizontal deck position when at rest.
- Enable the rider to perform aerial skateboarding-style tricks and standard snowboarding tricks.
    - Remains fully functional after sustaining repeated impact loading.
    - Is light enough to be lifted by the rider.
- Maintain tilt position regardless of applied impact loading so that the direction of the rider is not suddenly changed when traversing uneven or rough terrain
- Resist corrosion in an alpine environment
- Overall dimensions similar to or less than those of a skateboard so that the user

The work that has been undertaken to complete this thesis does not address all of these specifications. The primary scope of this thesis involves the design and optimisation of the board-to-skis mechanism connection. However, all of these overall requirements for the final design were kept in mind throughout the process to influence decisions involving the mechanism complexity, size and performance characteristics.

1.2 Mechanical Engineering Project Objectives: Linkage Synthesis and Design

This design task led to an investigation of mechanism design techniques and tools. Research was conducted with the intent to find resources to assist in the synthesis of a planar linkage mechanism that would satisfy the design requirements. The field of mechanism design is broad and some areas, especially regarding the design of precision point following four-bar linkages, are well-researched. Other areas within the subject of mechanism synthesis and optimisation present modern researchers with the opportunity to develop new techniques and tools to assist in the mechanism design process, as the existing information has either not been presented in a cohesive fashion or leaves the designer wanting for more efficient, user-friendly design helps. A review of literature, with a focus on planar linkage synthesis and dimensional optimisation, is presented in Chapter 2.

One of the two fundamental goals of this masters research was to compile existing tools and techniques, along with those created for this particular design task, to create a methodology and linkage synthesis assistance program for use by mechanism designers faced with problems of similar complexity to the Skiboard. The second goal was to design, analyse and optimise linkage mechanisms that would fulfil the design specifications for this product.

The methods and tools generated during this research have been explained within the context of the broader subject of mechanism design. In particular, they are not meant to replace existing methods developed by other researchers. Rather, it is hoped that this contribution will add to the existing collection of tools, enabling easier concept development for designers faced with complex tasks. Thus, it presents an overview of the types of tools that are available for different applications from a design perspective. As a secondary goal, the limits found in this context may inspire further research and development.

While the solutions to individually satisfy the motion and function requirements may be simple in nature, the task of considering both requirements at once is challenging and the tools with which to tackle such a problem are, in the author's experience, few and far between. For example, Kinzel references complex mechanism design in his paper on kinematic synthesis, but does not provide explicit design methods or specific synthesis instructions for the designer (Kinzel, Schmiedeler et al. 2006).

Mechanism design as it relates to under-constrained problems is the primary realm of interest explored in this thesis. The Skiboard design task is a prime example of such a problem. Specifically, it deals with a qualitative set of specifications that are difficult to quantify in a way that is solved in a straightforward fashion with existing techniques, equations or software.

Under-constrained problems are defined in this thesis as problems for which there is not one unique solution. (Hiroyuki 1999) Algebraically speaking, an under-constrained problem would contain a greater number of unknown variables than the number of equations available to relate them. Under-constrained problems must usually be solved by educated guesswork to remove some of the unknowns. Introducing “assumed variables” can give the designer a place to start, but the inappropriate selection of these values may lead to an impractical solution that might not move the design process any closer to a conclusion. (Norton 1992) Correcting for malfunctions based on the selection of “free choice” variables has the potential to add iterations and frustration to an already complex synthesis process.

Another way to approach under-constrained problems is to explore a range of possible solutions and decide, from the analysis of those options, which variables are most important to control or fix with assumed values. Making such assumptions can be valuable in creating a starting point for synthesis. The trade-off, however, lies in the risk of missing potential solutions by fixing certain variables in error.

Many real-world mechanism synthesis problem statements are under-defined, which means that most of the problems themselves are under-constrained. Keeping that in mind, it is important to consider synthesis methods that lend themselves to helping designers in these situations. Since the design of the Skiboard is a particularly under-constrained type of synthesis task, the following chapters explore the process undertaken for its design and present new suggestions for solution techniques to be used in the future.

1.3 Skiboard History

The most recent physical prototype of the Skiboard mechanism, referred to as Concept 0, is shown in Figure 2. Concept 0 consists of two coupled four-bar linkages with revolute joints connecting each of the links. This linkage design was found to have unique properties.

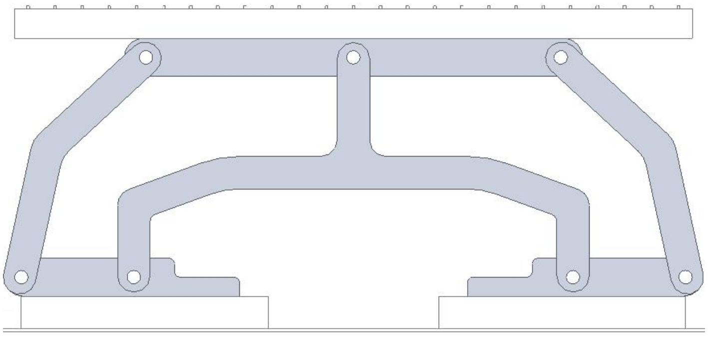

Figure 2: Concept 0 Mechanism

This mechanism's behaviour produced several desirable attributes that became requirements for all future iterations of the mechanism's design. First, this linkage provides the rider a large area of stability. In other words, the rider can comfortably stand in the centre of the board with the skis flat without needing to finely balance the board in its rest position.

The second favourable characteristic observed was the limited maximum angle of tilt experienced by the skis and the board, relative to the ground. While this angle was not small enough to prevent the rider falling off of the Skiboard when it tilted to its maximum angle, the presence of a limiting angle was decidedly important. To keep the rider stable, the line of force through his or her centre of gravity must pass through the stable base, or, in this case, between the skis. Extreme angles of board tilt beyond 25-30° would require enormous centripetal forces to keep the rider stable.

The Concept 0 mechanism also displayed a few unfavourable characteristics that would inspire future design iterations. The first and most significant unfavourable tendency was a sudden initiation of board tilt outside the area of stability, as shown in Figure 3. This sudden initiation from a resting stance to a ski angle of 27° leaves the rider with little control, especially when attempting to ride at a slow speed and carve gentle turns.

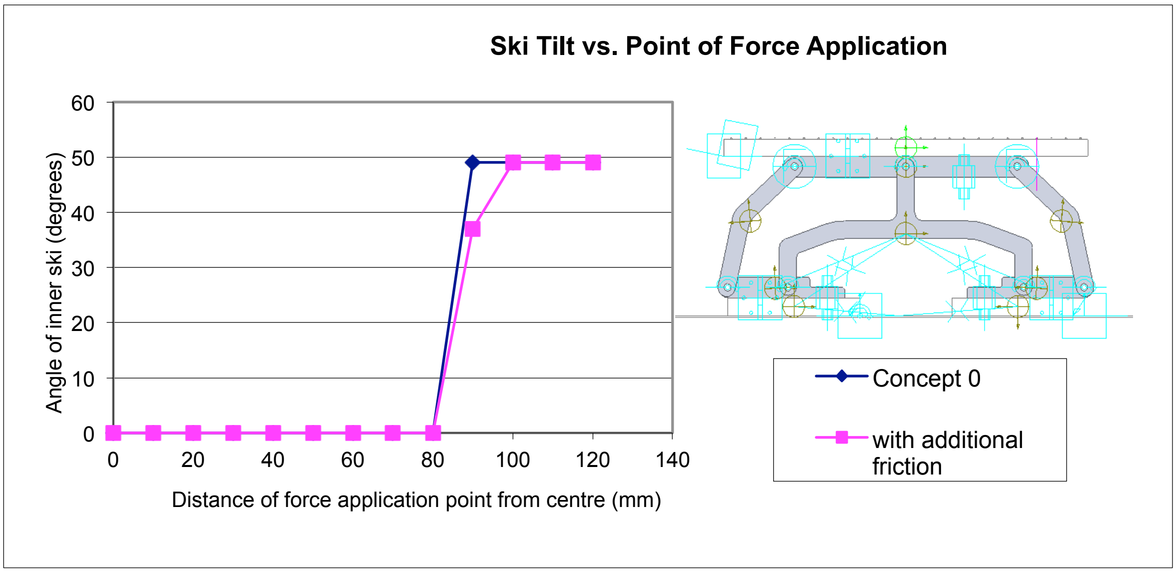

Figure 3: Concept 0 Ski Tilt

Second, throughout the mechanism's range of motion, there was a dissimilar angle of tilt between the skis and the board. Figure 4 shows that the ski on the outside of the turn radius, the right ski in the case of this test, is tilted approximately 10° more than the inner ski. There is also a large gearing ratio between the board and skis, approximately 1:2, which is undesirable because the feedback from the board under the rider would not closely match the radius of the turn he or she is carving.

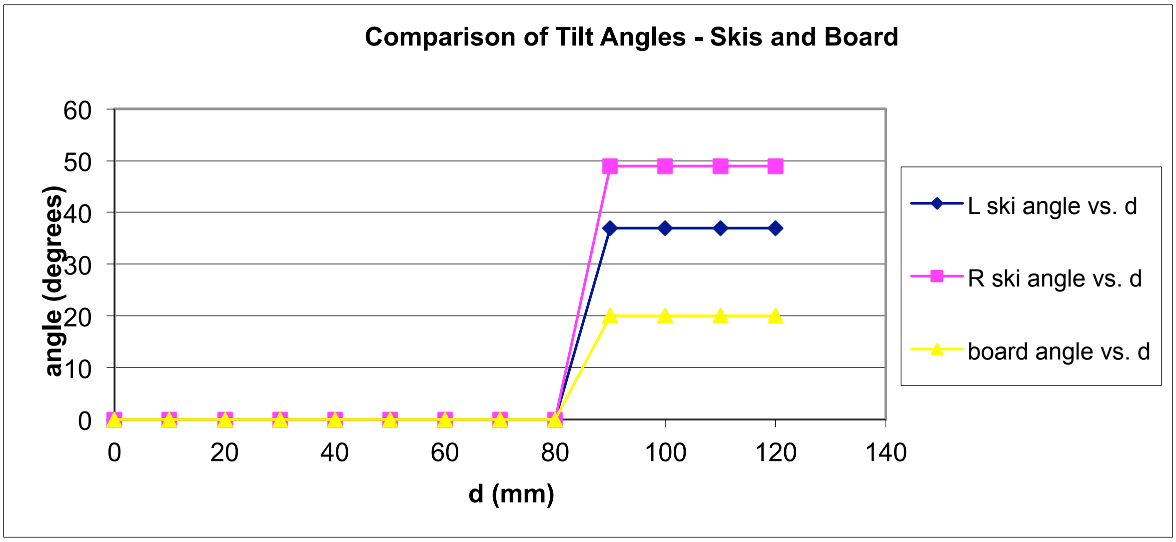

Figure 4: Concept 0 Comparison of Ski and Board Angles

Another unsatisfactory characteristic was the board's very large area of stability around the centreline. To initiate ski tilt, the rider would need to direct his or her weight towards the edges of the board and would require an extreme change in body position. In other words, this large "dead zone" cannot offer an exciting ride or produce turns under typical riding conditions.

To resolve these issues, another design concept, Concept 1, was explored using SolidWorks, and is shown in Figure 5. This concept showed the potential to produce the desired path of motion, but lacked practicality. The mechanism moves the board, but does not link the skis to the rest of the system.

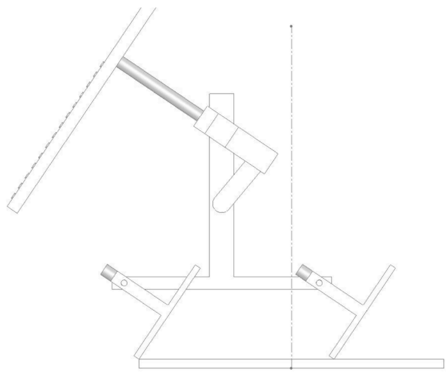

Figure 5: Concept 1 mechanism

In particular, the SolidWorks model assumes that the link responsible for the tilt of the board remains perpendicular to the skis for the entire range of motion. This assumption was made in an effort to simplify the design problem to focus on producing a desirable path of motion for the board and identify the input motion that would achieve such results. A more in-depth explanation of the "desired path of motion" for the board is presented in Chapter 5.

At the start of this research, discrete virtual testing (performed iteration by iteration) was repeated for this mechanism to verify previously obtained results. It also provided a way to validate virtual test setups that were used prior this research to ensure that designs which showed promise as suitable solutions did, indeed, behave as the test results predicted. Finally, it was important to determine whether the automated virtual test setup could be advanced and applied to future concept models.

1.4 Stages of New Product Development

1.4.1 Methodology Selected for Structuring Research & Design

A structured design methodology was chosen as a guide for this task, as is common practice in most engineering design situations. A product design methodology developed by M. R. Baxter (1995) was chosen to aid in structuring the flow of the design activities. It was decidedly suitable to this type of design task for several reasons.

First, this type of flow chart was created for designers faced with working on relatively simple products. While the design of the Skiboard linkage is, in itself, a complex undertaking, the product itself is comprised of relatively few parts and expected to possess only a few explicit design features. Second, the format of Baxter's flowchart makes it easy to follow the iterations in the design process and track the progress of a task.

The flowchart below, which has been adapted from Baxter, was used as a guide throughout this project. Certain steps in the design process were omitted from the chart (as shown) because the tasks associated with these steps did not fall within the scope of this research. In particular, the detail design portion of the chart and all design steps thereafter lie outside the present scope.

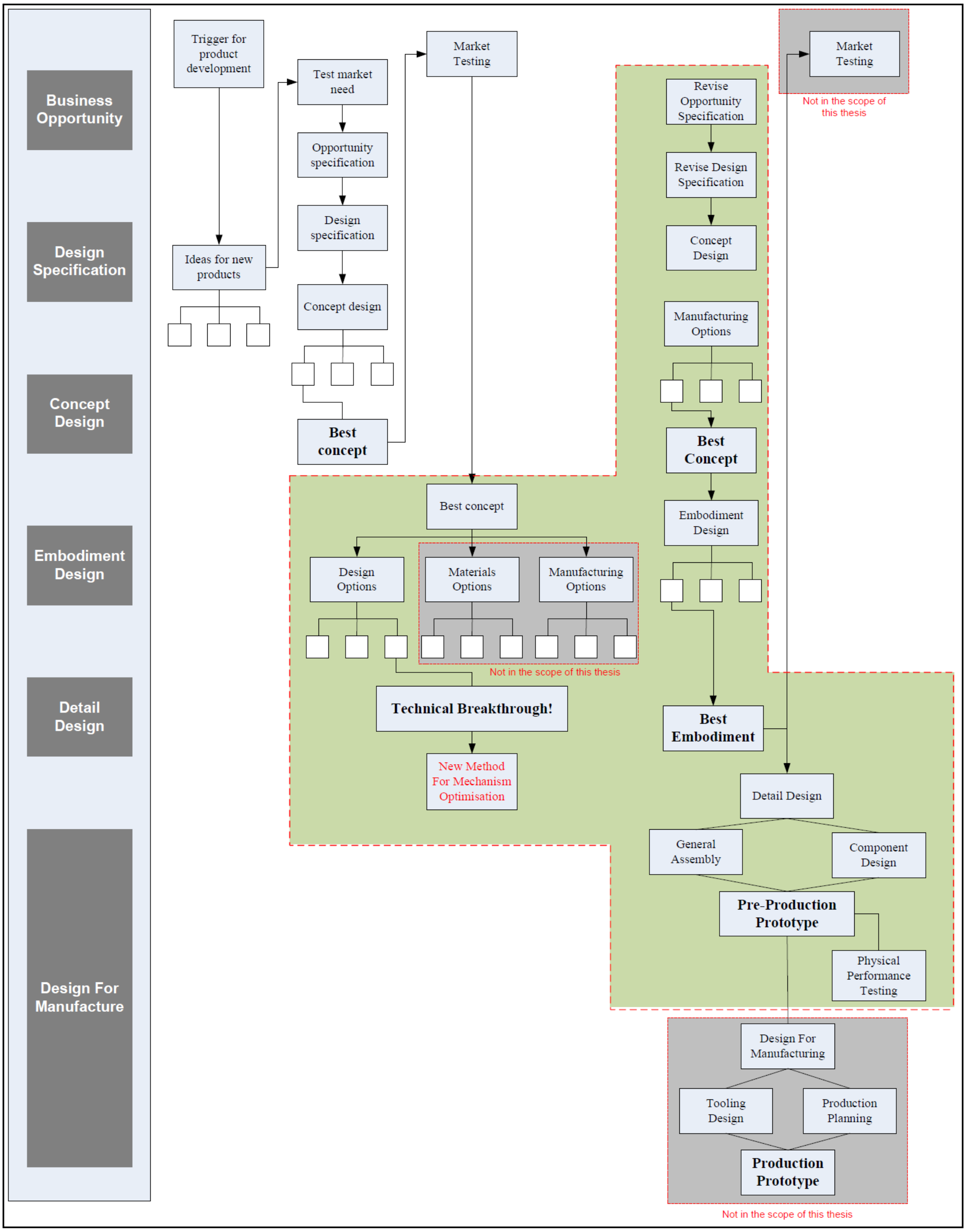

Figure 6: Product design flowchart adapted from Baxter

For the design specification stage of the design process, a specification format was required. The creation of a product design specification list was informed by Pugh (Pugh 1991), who recognises the importance of creating a detailed PDS at the outset of any design project. A modified version of his PDS model was applied at the outset of the design task. It was updated as the process progressed as more qualitative information about the Skiboard requirements became available.

1.5 Mechanism Design Task

To understand the design task that will be described in this chapter, it is necessary to first define the three types of functional requirements of mechanisms as they are defined in literature (Olson, Erdman et al. 1985; Erdman 1995; Uicker, Pennock et al. 2003; Pucheta and Cardona 2005; Mundo, Liu et al. 2006). This topic is covered in Chapter 2, but presented here in greater detail as an introduction to the material that follows.

The three classes of coordinated motion studied in kinematics literature are path generation, motion generation and function generation. The first and most widely researched functional requirement - path generation - is described as the "guiding [of] a point on a member along a desired path" (Ananthasuresh 2001). Path generation involves the tracking of a single point, or coupler point in the case of a linkage. Its problem definition excludes the orientation (or angle of rotation) of the output link. (Sedlaczek, Gaugele et al. 2005)

The second class of coordinated motion, called motion generation, involves "guiding the entire rigid body in a desired manner" (Ananthasuresh 2001). It differs from path generation in that all three dimensions of planar orientation are considered rather than the path of a selected point on that body. If the functional requirement of a mechanism concerns the (x, y) position of a point on that body as well as the moving body's angular orientation, it can be classified as a motion generation problem. Naturally, the addition of a third dimension of solution space increases the complexity of the synthesis from that of a path generation problem.

Function generation, the third class of coordinated kinematic motion, is defined as "the controlled correlation of an output motion to an input motion" (Kinzel, Schmiedeler et al. 2006). A function generator "achieves a desired relationship between a type of motion on one member and another type of motion on a second member" (Ananthasuresh 2001). This class of requirement concerns only one dimension, which is usually angular, between the output link and either the ground or another link in the mechanism whose coordinates are considered "ground" coordinates.

The chart below, which has been reproduced with slight modifications from (Olson, Erdman et al. 1985), concisely shows the differences between these three types (or classes) of requirements:

Table 1: Functional Requirements of Mechanisms (Olson, Erdman et al.)

Functional Requirement	Output for a Planar Mechanism	Output link…
motion generation	3-DOF output	is a floating link
path generation	2-DOF output	is a floating link
function generation	1-DOF output	rotates about or slides with respect to ground

The design of the Skiboard involves two of these classes of coordinated motion: motion generation and function generation. For this task, importance cannot be given to one of these two classes over the other because both are necessary for the mechanism to function properly. What results is a complex design problem.

There is a wealth of existing research on path generation, as was discussed in the chapter on the literature review. Point path problems can be solved with the help of linkage synthesis software (such as Watt). For point path solutions involving six links or less, optimisation can be carried out mathematically without much expense.

The design process used and the approach to mechanism design, rather than just the design tools themselves, are important to successful design outcomes. From research and experience with the current design task, the need for a comprehensive, iterative mechanism synthesis and optimisation methodology has become evident. The process presented in this thesis, created to fill this gap in the design process, aims to achieve these basic goals:

1. Involve the designer at all stages in the design process and provide an interactive solution environment.

2. Inspire creativity and guide the designer – the driving force behind the solution of the problem – to a solution that best satisfies the criteria according to the design constraints.

3. Provide guidelines and solution aids that will not require the designer to have extensive programming knowledge or specialised programming skills, recognising that those who are gifted in design and mechanics do not necessarily have a programming background.

The first goal of this project, to keep the mechanism synthesis and optimisation environments as interactive as possible, is difficult to fulfil when attempting to provide solution tools for such complex problems. Most of the recent research with regard to mechanism synthesis and optimisation has yielded very efficient and accurate solution capabilities, but has largely either removed the designer from the intermediate process or required that person to possess quite advanced programming skills and/or skills in converting linkage configurations into numerical matrix form.

Clearly, as with all engineering solutions, creating an interactive process will compromise the designer's ability to search the entire design space for solutions. However, this trade-off will not necessarily mean that a less suitable solution will be found considering that even the most thorough solution search methods miss portions of the design space. It can also be argued that an easily-usable mechanism design process will not replace other design assistance tools. Rather, it will reach an unreached portion of the population of mechanism designers who do not possess the skills or resources to program possible solutions or who simply do not feel that the use of such programs will increase their potential to find a suitable solution to a motion or function problem.

This research introduces a segmented, iterative design process, created to make mechanism synthesis and optimisation problems easier to solve by guiding the designer through crucial stages of the process, aiding in the identification of the fundamental design specifications and providing tools (and suggestions for the use of existing tools) that might be helpful in synthesising and, ultimately, optimising a solution. A thorough explanation of this process will be given as part of the chronicle of the Skiboard design experience, as many of the ideas behind this design process were inspired by the challenges presented during this design task. The first major advance in the design of the Skiboard involved segmenting one complex task into sets of simpler design problems according to its list of Product Design Specifications (PDS).

1.6 Research Deliverables

This thesis will explore the topic of modern mechanism synthesis and optimisation in the context of designing an internal mechanism for this mechanical system (the Skiboard). The concepts and virtual prototypes resulting from the design process will be presented and discussed. Where possible, the developments made with this project have been discussed in the global context of mechanism design, as the goal of this research is not only to innovate within the snowsports industry, but also to inform and aid other designers and researchers who are faced with complex, under-constrained design tasks of a similarly challenging nature.

The design deliverables for the successful completion of this project are three fold. The first is a refined PDS for the Skiboard, informed by research, trial and error and experimentation with virtual models. The second is a virtual, iterative testing procedure for use by designers faced with complex linkage synthesis tasks. The third is the development of mechanism solutions for the Skiboard.

These deliverables are presented in the chapters of this thesis according to the following structure:

Chapter 2: The findings of a literature review on mechanism synthesis and optimisation are presented in this chapter. The relative merits and weaknesses of existing techniques and software are also discussed.

Chapter 3: This chapter presents an experimental process for synthesising linkage solutions and generating solution concepts, called Solid Model Atlas Creation (SMAC). SMAC was developed and used specifically for the design of the Skiboard mechanism, but can be applied in many other complex design situations.

Chapter 4: This chapter presents a concept for a software package to assist linkage designers explore solutions to black-box synthesis problems, called Parametric Sketching and Evolutionary Optimisation (PSEO). It is a more advanced concept than SMAC designed to function beyond its limitations, involving the automatic analysis and evaluation of experimental results.

Chapter 5: This chapter follows the concept design process for the Skiboard and the refinement of the product design specifications.

Chapter 6: This chapter presents models developed for the analysis of forces and anthropometric considerations during the design of the Skiboard.

Chapter 7: This chapter presents the conclusions of this research and suggestions for areas of future research, development and Skiboard-related design.

It is necessary to highlight the fact that the design process for the Skiboard, as with most engineering-related processes, is iterative in nature. Circular referencing is difficult to avoid in the explanation of such a process. Therefore, for added clarity, a glossary has been provided to define terms that have been used in more than one chapter and might be difficult to understand. A concise explanation of the different design phases of the Skiboard can also be found in Appendix A, where the concept number given to each phase along with a rendering or photograph of the design phase has been provided.

Chapter 2.

Optimal Mechanism Synthesis Processes

Mechanism synthesis is the creation of a linkage or other type of mechanism to accomplish a required task or tasks. The “required task” will be referred to, henceforth, as a functional requirement. There are three types of functional requirements that a mechanism designer might desire to accomplish with the use of a mechanism. For more complex problems, called compound mechanism synthesis problems, more than one functional generation requirement must be satisfied. The three types are: 1) path generation; 2) motion generation; and 3) function generation.

Path generation, the most widely studied kind of type synthesis, involves moving a coupler point (or point on the output link) along a path that is prescribed by the designer. The path generated by a coupler or coupler point can either be defined by a function, expressed in equation form, or by a set of precision points. The x and y positions of the coupler point in a Cartesian system are relevant in path generation tasks, which makes them two degree-of-freedom problems. (Uicker, Pennock et al. 2003)

Motion generation, which is required for many design tasks, involves moving the coupler along a path while controlling its orientation. Since this type of functional requirement concerns the x and y position of a couple point as well as the coupler’s angular orientation, θ, it is a three degree-of-freedom kind of problem. Figure 7 provides a visual representation of this requirement.

Function generation causes an output link to rotate, oscillate or reciprocate as either a function of time or a function of input motion. (Uicker, Pennock et al. 2003) Typically, function generation problems involve rotary-rotary transmission or “a specified output from a given rotary input”. (Molian 1997) This type of generation can be expressed with two variables: θ_1, describing the angle between link 1 and the ground, and θ_2, describing the angle between link 2 and the ground.

Figure 7 clarifies, schematically, the differences between the three requirements. It shows a single link in blue at its starting position and in purple at an intermediate position, fulfilling a specified functional requirement. For path and motion generation, the coupler point is indicated by an arrow. The output link is shown in two positions in the path, denoted by coordinates subscripted 1 and 2.

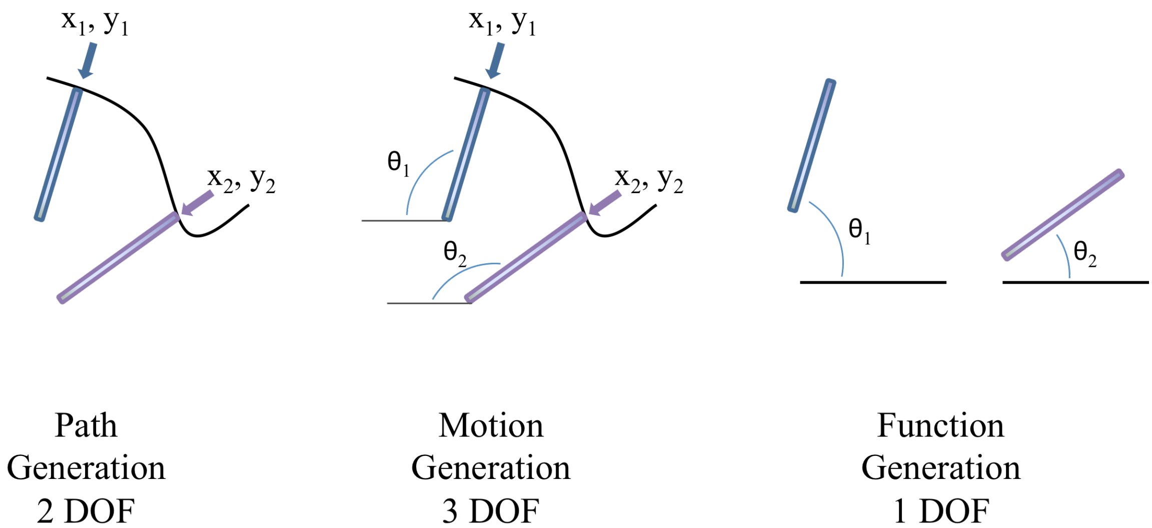

Figure 7: Path, Motion and Function Generation

The Skiboard required the synthesis of a compound linkage, responsible for generating a motion and a function. This chapter does not contain references to any software packages or tools by other researchers that deal specifically with this kind of compound design task, as none have been found to date. Some programs are capable of potentially being programmed to serve this purpose, but such software requires the user to be intimately familiar with a specific programming language.

The synthesis programs that provide a user interface deal with single-input synthesis problems and present a range of possible linkage as solutions include, but are not limited to, the following: WATT, SAM, LINCAGES 2000, SYNTHEITCA and SYMECH. Using these programs, it is not possible to connect several discrete linkages and analyse of their interactions. Some examples presented in sections to follow will give an overview of the functionality of existing synthesis software.

2.1 Mechanism Synthesis and Optimisation

Before beginning to synthesise suitable mechanisms for the Skiboard, a literature review of mechanism design, synthesis techniques and optimisation techniques and tools was conducted. The majority of existing literature deals with the synthesis and optimisation of four-bar linkages, but many of the techniques presented can be applied to more complex linkages. Few authors discuss synthesis techniques to assist a mechanism designer with choosing an appropriate type of mechanism for a desired path of motion, citing the creative demands on this part of the process. (Sardain 1997; Saxena 2005)

A majority of the literature deals with analysis or optimisation of link lengths for mechanisms of pre-determined configurations, a relatively minor design problem as the configuration is given. These modest design problems reflect a situation where specific configurations were suitable and merely optimised to satisfy a task. The problem confronted here is synthesis and design of a wholly new mechanism to meet a set of required points and motions while operating within the constraints.

It has become apparent, through conducting this literature survey, that there is an opportunity for more research and the development towards a more modern and interactive methodology to assist in the design synthesis of novel linkage-type mechanisms. A review of relevant existing literature and field-related terminology is first presented as background to the research conducted for this thesis. It is followed by an examination of existing tools and how they may fit into a design synthesis framework.

First, it is necessary to define some of the often-used terminology in the study of mechanical systems. The term *synthesis*, which is frequently and appropriately interchanged with the term *design*, is the process of "prescribing the sizes, shapes, material compositions and arrangements of parts so that the resulting machine will perform the prescribed task." (Uicker, Pennock et al. 2003) This rather broad definition can be narrowed for the field of research concerning mechanism synthesis to include only the arrangement of parts and the determination of their relative sizes.

Mechanism synthesis has traditionally been divided into two categories. Specifically, *type synthesis* and *dimensional synthesis*, where type synthesis refers to the shape and arrangement of parts and dimensional synthesis refers to their size. These terms are defined and discussed in more detail in Section 2.2.1.

The word *optimisation* as it relates to mechanism design is a bit more difficult to consistently define. In the case of path synthesis problems, Sancibrian et al. (2004) define optimisation as "the minimisation of an objective function, called synthesis error function." By this definition, optimisation refers to how well the solution satisfies its objective. For example, if a mechanism is synthesised to follow a prescribed path, the error between this path and the actual path of the coupler point must be minimised for the solution to be optimised.

Alternatively, the task of optimising a design can involve fitting the solution to a set of criteria or rules rather than minimising a single objective function. This rules-based approach to optimisation is generally more applicable to complex synthesis problems with changing or under-defined criteria, as well as those involving the fulfilment of more than one functional requirement. In the case of the Skiboard, this approach to design optimisation is better suited to finding a solution than using classical optimisation techniques alone.

In manufacturing terms, the process of optimising a solution also includes Design for Manufacture (DFM) considerations. However, the scope of the review presented here is limited to considering only the topological and dimensional characteristics of linkage mechanism synthesis. Some manufacturing issues were designed for inherently during the physical prototyping phase.

The altering of linkage shape for ease of manufacture or the explicit consideration of DFM when establishing the design criteria will not be presented as part of this discussion of the early-stage mechanism design process. The scope of this review will be contained to the topics appearing in the systematic design table, Table 2, compiled by D.G. Olson (Olson, Erdman et al. 1985):

Table 2: Systematic mechanism design

I. Problem Definition
   - A. Topological Requirements
     1. Nature of motion (planar or spatial)
     2. Degree of freedom (number of inputs)
   - B. Functional Requirements
     1. Number of distinct outputs
     2. Task to be accomplished by each output
     3. Complexity of each task
   - C. Constraints
     1. Dimensional constraints
     2. Inertial constraints

II. Type Synthesis
   - A. Topological Synthesis
     1. Enumerate basic kinematic chains (BKCs) satisfying topological requirements.
     2. Enumerate "basic mechanisms" derivable from each BKC, by assigning the ground link.
   - B. Topological Analysis
     1. Determine type of freedom (if d.o.f. is greater than one) and distinct ways of applying input(s).
     2. Identify possible output(s) to satisfy functional requirements.
     3. Assign joint types based on specified inputs and functional requirements.
     4. Evaluate each mechanism based on functional requirements.

III. Dimensional Synthesis
   - A. Kinematic synthesis—For a given type of mechanism, determine dimensions based on functional requirements.
   - B. Kinematic analysis—Evaluate mechanism based on dimensional constraints and kinematic (static) criteria.
   - C. "Dynamic" Analysis—Evaluate mechanism based on inertial constraints (kinetostatics, kineto-elastodynamics, time response, etc.).

Dimensional synthesis and optimisation are symbiotically linked. As a result, linkage optimisation could, in most cases, be referred to as dimensional optimisation. For the purposes of this thesis, the subjects of linkages optimisation and dimensional optimisation are considered to be one and the same.

It is worth noting that robustness may also be considered as a factor when optimising mechanisms. Robust designs aim to perform their intended function in the presence of disturbing "noise" factors, environmental or otherwise. For linkages, the most significant sources of noise are manufacturing tolerances, deformation induced by loading and wear/creep. Therefore, robustness as it relates to mechanism design can be defined as "minimal sensitivity to variations" or, in other words, minimal dimensional sensitivity. (Da Lio 1997)

Depending on the design task, it can be difficult to ensure robustness. However, this design factor is a critical consideration during the product design process. It can be accounted for in a quality function, also known as a fitness function, as presented in DaLio's work, but can also be introduced earlier in the design process by considering a few general guidelines. According to DaLio (1997), the following factors contribute to a linkage being particularly sensitive or lacking in robustness:

1. *Highly asymmetric and/or elongated configurations* - These types of configurations enhance link variations and small sensitivities can result in mechanisms that display unstable and unpredictable behaviour. Note that these configurations can be constrained in the design by placing limits on length, number, specific singular configurations, etc.

2. *Singularities due to improper synthesis* - Singularities can occur in positions that result in the collinear positioning of two links. It can also occur if the input force

produces lock-up or aligns itself over a “tipping point” on the mechanism’s stable base. Any of these situations can result in the next movement of the mechanism being difficult or impossible to predict, rendering it unstable and non-robust.

3. *Complexity.* As each link adds noise sources and finer tolerance requirements to the design, complex mechanisms are less robust than simpler ones.

A fourth factor that is not often considered, but is worthy of consideration when designing for robustness is the type of kinematic pairs chosen to create a mechanism. One basic guideline to follow in making a mechanism more robust is to use lower pairs, joints that have surface contact, in favour of higher pairs such as cams and gears. Lower pairs, by nature of the fact that they have surface contact rather than line or point to surface contact, are less sensitive to manufacturing tolerances and changes to joining or contacting surfaces due to environmental and operational conditions (Kyung and Sacks 2006).

These robustness factors can add to the constraints placed on the design problem. Some of these constraints could include an upper limit on the number of links or a symmetry requirement. However, it is note-worthy to consider that adding constraints will result in compound the complexity of the sythensis problem.

2.1.1 Historical Review of Mechanism Research

In 2003, researcher T.S. Mruthyunjaya presented a review of literature to date on the subject of the kinematic structure of mechanisms. In his review, he identified trends in research on the subject over four decades, which follow highs and lows in approximately ten-year cycles. The histogram in Figure 8 shows the number of publications per year on the kinematic structure of linkages and illustrates the relative pattern in linkage research on the whole.

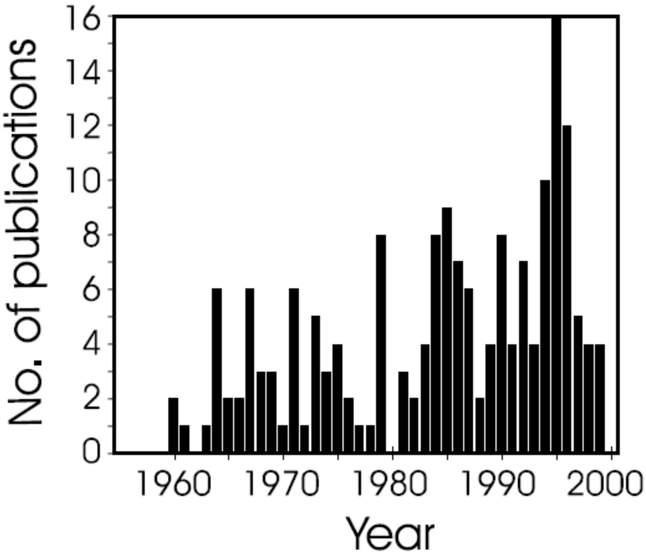

Figure 8: Trends in Publication on the Kinematic Structure of Mechanisms (Mruthyunjaya 2003)

The history of human interaction with mechanisms and mechanism synthesis is long and certainly predates the 1950 start date appearing in the image in Figure 8. Many of the famous works of Leonardo DaVinci, for example, include illustrations of inventions including novel linkages and other mechanisms that went on to be useful in the centuries following their time. However, according to recent research on the subject, the start of scientific investigation into the topic of mechanism synthesis and associated design processes began in the 1950s with the systematic analysis and cataloguing of four-bar mechanisms.

No review of graphical mechanism synthesis methods would be complete without the mention of the Hrones-Nelson Atlas, developed in 1951. This atlas, referenced many times in this text, is a compilation of over 7000 coupler curves produced by four-bar, crank-rocker linkages with varying dimensional properties. A sample page from this atlas is shown in Figure 9. Each page contains a number of possible coupler curves for a specified four-bar mechanism. The length of the crank is unity in every case and the other three link lengths are specified as A, B and C. The coupler curves are created by adding a number of coupler points. These are indicated by small circles on the chart in Figure 9. Hrones and Nelson mapped coupler curves for 730 dimensional combinations.

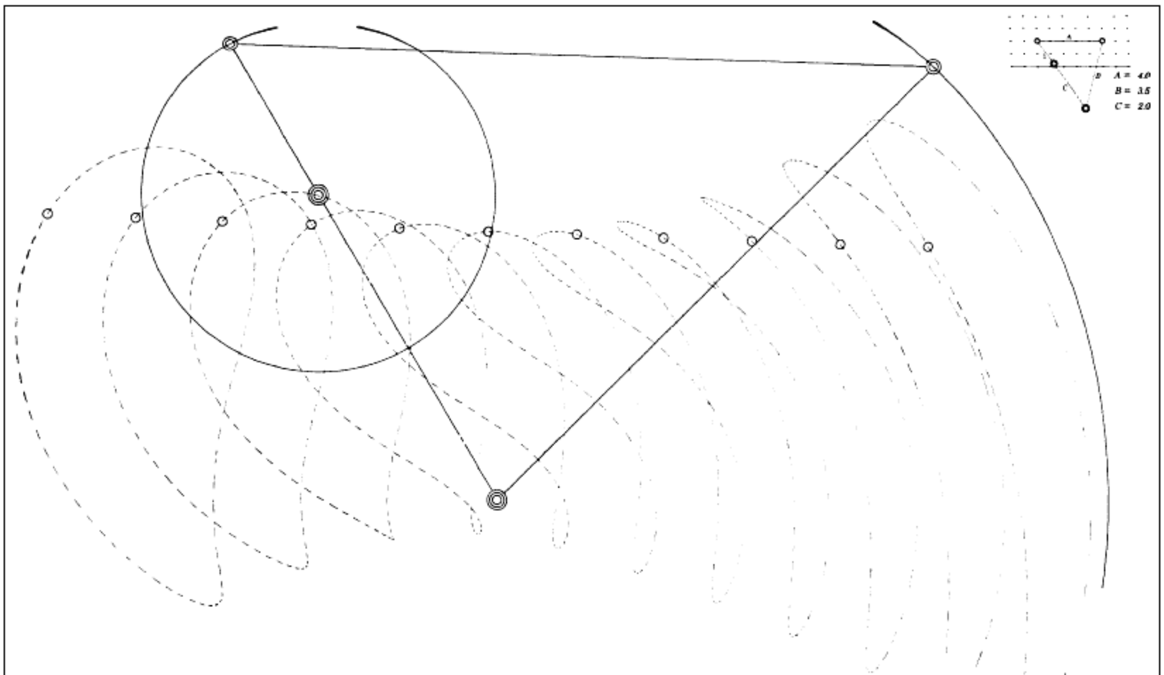

Figure 45.—Paths of 11 points on the coupler (horizontal) link are plotted through one cycle. Dashes indicate equal time intervals. From John A. Hrones and G. L. Nelson, *Analysis of the Four Bar Linkage* (New York, 1951, p. 635).

Figure 9: Four-Bar Linkage Coupler Curves (Hrones and Nelson 1951)

Almost 60 years after its publication, the atlas remains one of the best sources of coupler curves and an invaluable tool for mechanism designers. The coupler curves from this atlas are contained in most graphical synthesis computer packages, such as SWORDS (Medland and Mullineux 2000). Interestingly, despite the advent of modern computing and design programs over the last twenty years, a more complete collection has not since been established.

Most researchers agree that the topic of analytical mechanism synthesis was pioneered by Freudenstein in the 1960s (Fox and Gupta 1973). Other well-known mechanism researchers such as Burmester, credited with the founding of graphical mechanism synthesis, were developing graphically-based synthesis techniques nearly a century earlier

(Ceccarelli and Koetsier 2006). Interest in the subject peaked and waned until the mid-1970s when the advent of computer systems stimulated a rebirth in interest in the subject of mechanism synthesis with the creation of software such as KINSYN, LINCAGES and RECSYN. With each new step forward in the problem solving capabilities of computers, mechanism synthesis-related research has followed with investigations into possible applications of computer power to aid in the design process.

Since the early 21st century, research in the field of mechanism synthesis, specifically linkage synthesis, has taken many directions. Most researchers with an interest in creating helpful mechanism synthesis tools face the challenge of providing interactive computer graphics. For the effective application of design concepts for linkages, "the designer requires visual representation" of the solution space (Mlinar and Erdman 2000).

Along with the adaptation of analytical and graphical methods for a computer-based interface, several other design techniques have been researched, including experimental methods involving automated search algorithms. The challenge for the development of highly automated software is maintaining a usable design interface that can provide visual feedback. Graphical solution methods, for the reasons of being user-friendly and providing immediate and useful visual feedback, remain relevant to mechanism designers in the age of computers. Thus, the future of synthesis software development is likely to see the integration of graphical methods with other analytical or numerical solution techniques.

2.1.2 Literature Review Scope and Structure

In the sections to follow, linkage synthesis and optimisation research, tools and processes are reviewed. Special attention will be given to topics directly relating to the design of the Skiboard, which relate to compound mechanism synthesis from under-constrained problem statements. The topics of compound mechanisms and under-constrained problem statements are discussed in more detail later in this chapter.

2.2 Type or Topology Synthesis

2.2.1 Type Versus Dimensional Synthesis

In the area of mechanism design, the process of determining a mechanism's topology is referred to as "type synthesis". The latter stage of determining the size of the links and of the mechanism as a whole is called "dimensional synthesis". Traditionally, these two stages of the design process, first defining the topology and then defining the optimal dimensions, are treated as distinct steps.

Some texts divide type synthesis into two stages, thereby defining mechanism design as a three-phase process consisting of type synthesis, number synthesis and dimensional synthesis (Hain 1967; Erdman, Sandor et al. 1997; Uicker, Pennock et al. 2003). In this case, type synthesis refers to the kind of mechanism selected, such as linkage, geared system, cam system, or belt and pulley system. Number synthesis is defined as dealing with the number of links and the number of joints or pairs that are required to obtain a certain number of degrees of freedom. According to Uicker, "number synthesis is the second step in design following type synthesis (and) the third step in design...is called dimensional synthesis" (Uicker, Pennock et al. 2003).

While this traditional approach provides the designer with a step-by-step process to follow, it can make the task of mechanism synthesis seem misleadingly simple. What is overlooked in making synthesis a clear-cut two- or three- step process is the fact that any synthesis stage can radically change the behaviour of the mechanism being analysed. Thus, the steps and problem complexity in this under-determined design optimisation problem are conditional or prior steps, where the simple process map implies an independence that does not exist.

In the case of mechanism design, and especially in the case of linkage design, defining the topology of a mechanism without any dimensional information is insufficient for determining whether or not a solution satisfies the functional requirement (Fang 1994). A mechanism design concept usually cannot be fully described without at least approximate dimensional information. At minimum, it requires the approximate size ratios between the links. For example, the behaviour of a simple four-bar linkages change dramatically depending on the dimensional ratios of the links. The Hrones and Nelson Atlas provides clear examples of the way in which dimensional characteristics change the behaviour of linkages. The atlas presents 7,000 paths of motion produced by four-bar linkages that vary only in dimensional proportions.

As W. Eugene Fang wrote in his paper on simultaneous type and dimensional synthesis (Fang 1994):

> *"The term conceptual design will not be synonymous to type synthesis in this paper. The term conceptual design is defined to cover both type synthesis and whatever dimensional synthesis is necessary to ensure that the functional requirements can be met."*

The same term usage will be true in this thesis.

Conceptual mechanism design consists of type synthesis, which involves the determination of the number and arrangement of the links, and at least approximate dimensional synthesis. There is agreement among researchers that the conjoint use of these stages is necessary for the successful early-stage conceptual design of mechanisms in the early design stage. (Sardain 1997; Liu and McPhee 2005; Pucheta and Cardona 2008)

An example methodology for optimal mechanism design, developed by Pucheta and Cardona (2008), is shown in Figure 10. The flowchart they present highlights the interconnected nature of early-stage dimensional synthesis (referred to as initial sizing) and type synthesis.

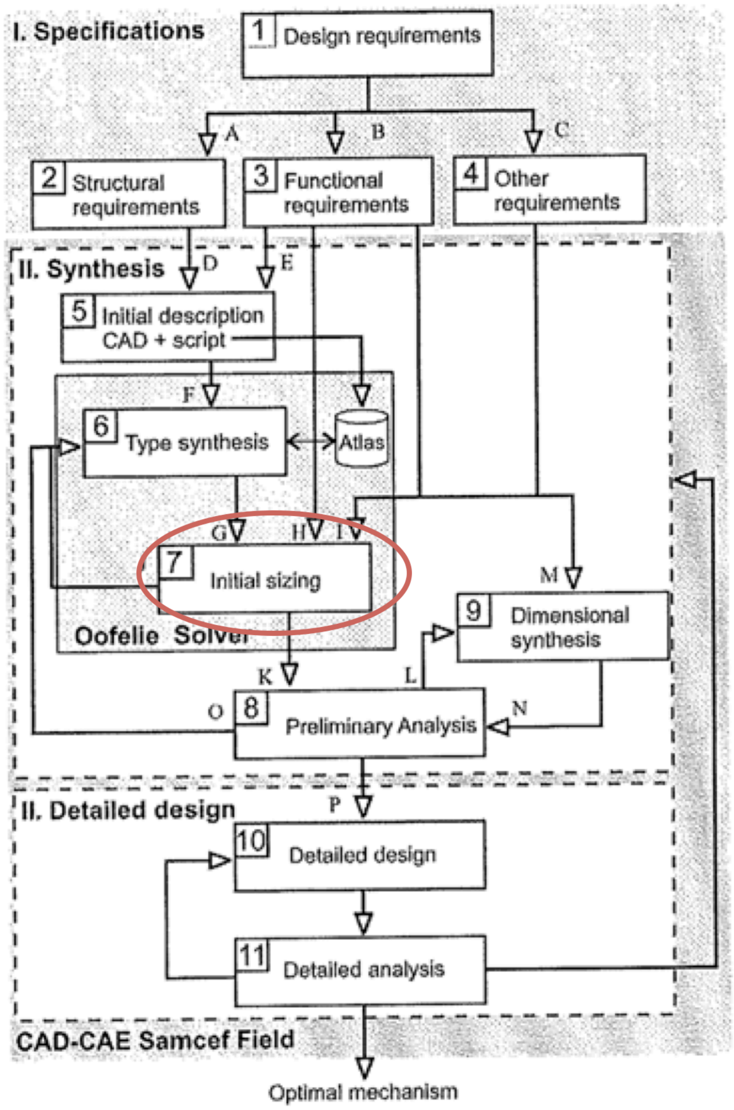

Figure 10: Method for optimal design (Pucheta and Cardona 2008)

The optimisation phase of the mechanism design process, performed immediately following conceptual design, involves the thorough synthesis of optimal link dimensions. For simple linkage design or for particularly well-constrained problems, dimensional synthesis and dimensional optimisation can occur simultaneously. However, for most problems, it is necessary to establish approximate link dimensions while deciding on the type and leaving the optimisation process for later.

The tools and design strategies developed in this research treat type synthesis as the creatively-inspired first step in an iterative concept development process. Each design iteration involves some dimensional synthesis to determine whether or not dimensional configurations of the type of solution proposed will satisfy the design criteria. Tools have been developed in this research to aide in the efficient execution of this process and will be presented in Chapter 3 and Chapter 4.

2.2.2 Type Synthesis Methods

Type synthesis, and number synthesis if the two are considered separately, is a complex topic that is largely left out of textbooks. The recent textbook by Uicker (Uicker, Pennock et al. 2003) briefly defines type and number synthesis, but devotes "the balance of the chapter" on the synthesis of mechanisms to dimensional synthesis. This imbalance occurs because synthesis is a black-box problem of sorts.

While there are opportunities for catalogues of mechanisms, CAD software, and computer-based search programs to aid the designer, this first step in the process is, in large part, dependent upon the creativity, problem-solving abilities, persistence and experience of the designer (Tao 1964). In many cases, the optimal design of a mechanism involves meeting requirements that are based on sensory feedback or approximate paths of motion. There are, therefore, difficult to quantify or define explicitly.

A. Erdman, the author of many texts and reviews on the subject of mechanism design, summarised type synthesis techniques in 1995 (Erdman 1995) as follows:

"Two approaches have been developed for type synthesis of mechanisms. The first approach, still the primary source of mechanism design, is the creation of atlases of mechanisms grouped according to function. The second approach involves either the abstract representation of the structure of the mechanisms or the symbolic representation of the functional aspect of mechanisms. This approach is more systematic, but requires skill to envision how abstractions of potential topologies can be presented to the engineer in a meaningful way." (Erdman 1995)

This statement still provides a good understanding of the topic a dozen years later, although advancements towards integrating the creation of atlases and systematically searching for solutions have recently been made (Ding and Huang 2007).

Atlases (Hrones and Nelson 1951), which are essentially catalogues of linkage configurations and their kinematic characteristics, have been present in the field of linkage design since the advent of the 1951 Hrones and Nelson Atlas. This atlas is still used for inspiration today and has been digitised so that it can be incorporated into linkage synthesis software. Collections of solved problems to provide example solutions and atlases integrated with direct search software remain some of the best tools with which to approach early stage type synthesis problems. However, there is a growing need to find new ways to use or integrate this catalogued design approach with other methods, especially for novel problems with no explicit prior design approach or history.

Commercially available software such as LINCAGES-4 (Wang and Yan 2002) and WATT (Draijer and Kokkeler 2002) can provide inspiration to a designer who wishes to find a path-generating linkage. These types of programs suggest possible linkage configurations to follow a user-defined path. However, the solutions are limited primarily to 4- and 6-bar planar linkages. LINCAGES-4 employs graphical Burmester theory techniques, which are explained in more detail in Section 2.3.2, to find linkages that will, as nearly as possible, trace a given path. The WATT program, developed by Heron Technologies, can synthesise linkage solutions for path and motion generation problems. It has the capability to synthesise planar linkages with up to eight links, although, as will be discussed shortly, it is not necessarily well-suited to every synthesis problem involving linkages of less than eight links.

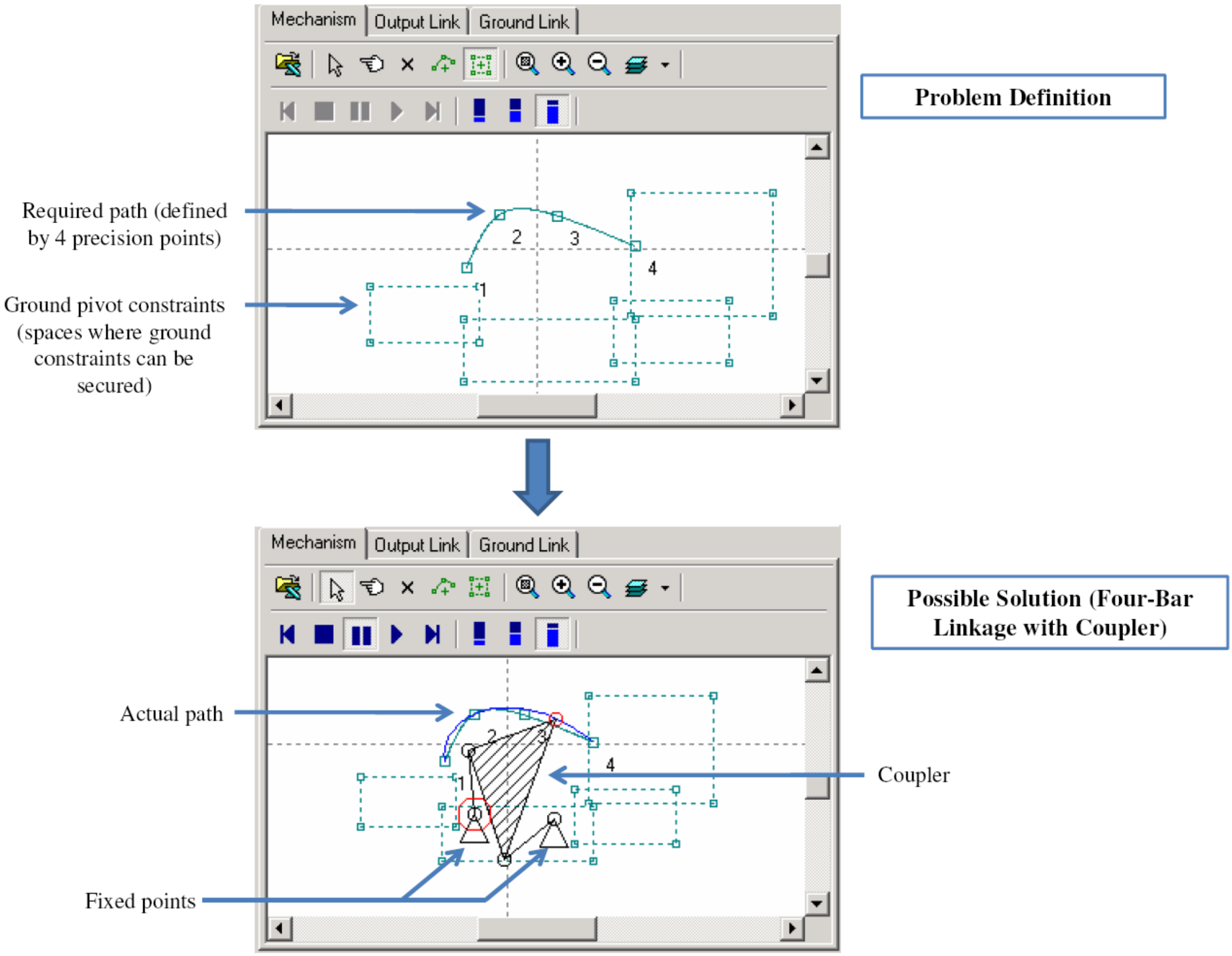

Figure 11: WATT program synthesis of a four-bar linkage

The screenshots in Figure 11 show a sketch of a required path of motion, given by the designer in WATT and defined by four precision points, and green squares delineating spaces in which stationary links may be placed. The window on the right contains a possible linkage solution. The example problem shows a relatively simple four-bar linkage synthesis to demonstrate the program's functionality.

Figure 12 shows a list of possible solutions that was developed by the program to solve the synthesis problem displayed in Figure 11. The solutions are listed in order of fitness, the top solution being the "closest" to the desired solution. More specifically, the path error (or the deviation of the actual path of the synthesised solution from the required path) is calculated in the following way: "Deviation is measured as distance between a path point and a point on the curve with the same relative path position." (Draijer and Kokkeler 2002)

The "total" values in the right-hand column of Figure 12 indicate the overall fitness value of the corresponding solution linkage. Values close to zero indicate good fitness between the specified path and the actual output path according to a comparison of the two paths on a point-by-point basis. It is, essentially, the measure of the difference between the two paths using a discretised fitness function.

The type of rigid fitness rule used by WATT, which takes only path fitness into account, may not be well-suited to problems with other sensitive requirements not accounted for by such an equation. For example, in the case of the Skiboard, a linkage that produces a path curve with concavity fluctuations through the desired range of motion would be ill-suited as a solution. However, a program like WATT could suggest such a linkage as a good-fit solution because fitness functions used in these programs do not discriminate between high- and low-order output curves. They only express an average goodness of fit over the entire range of motion rather than a shape comparison.

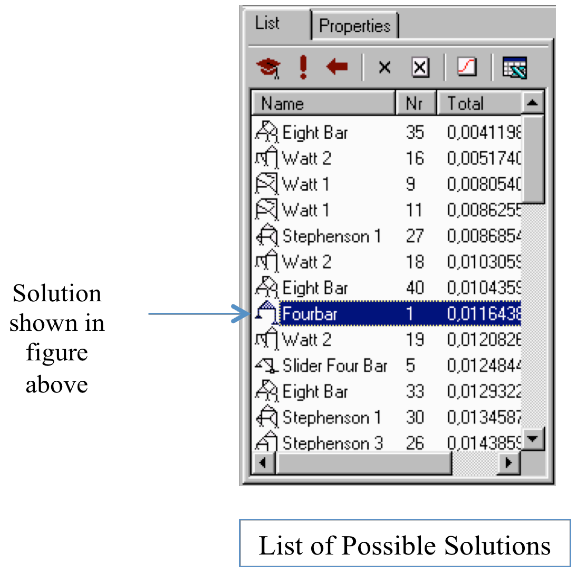

Figure 12: Screenshot of Solution List Window in WATT

While programs like WATT are relatively user-friendly and helpful in generating candidate solutions to a problem, there are several obstacles that prevent many designers from relying on them throughout the synthesis process. First, as mentioned previously, defining constraints within these programs is difficult and often results in the designer being presented with impractical solutions that do not fit within the available design space. Their usefulness is thus limited to design problems with few constraints on the design space and minimal complexity.

In the case of the Skiboard linkage design, programs like WATT were ill-suited to aiding the synthesis process for several reasons. Primarily:

1. They do not allow the user to specify that the input and output link are one and the same, as is the case with the Skiboard. A conjoined input/output link design problem such as this is a particularly complex and unique type.
2. They cannot automatically synthesise compound linkages in an efficient way. There is no way for the interactions between two closed-loop linkages to be analysed in the program's interface.

3. They cannot solve function generation problems, which the Skiboard and many relevant mechanism design tasks require. One popular practical application of a function generator is the Ackermann steering linkage used in vehicles. (Simionescu, 2002)

Since the publication of Erdman's literature review on type synthesis, Pucheta and Cardona (Pucheta and Cardona 2005) have combined both the atlas and the systematic search approach by creating a computer-based search program to match functional requirements to candidate linkages included in an atlas (Pucheta and Cardona 2005). The atlas, digitized by L. Tsai (1996), can be integrated into such search programs because the kinematic chains it contains are enumerated (or codified) using Graph Theory (Tsai 2001). Graph Theory provides a numerical nomenclature by which "all mechanisms can be generalised from an enumeration of revolute-mechanisms" (Pucheta and Cardona 2005). For further background on the topic, Schmidt and Chase (2000) provide in-depth explanations of Graph Theory.

The work of Pucheta and Cardona has taken the field a step forward in automating the search for optimal mechanism topologies, but still leaves the designer a critical step removed from the synthesis process. Since the Graph Theory representation of the solution linkages cannot automatically be transformed into a structural representation or visual form that looks similar the real object, the designer must be familiar with the nomenclature. Additionally, there is still no direct design synthesis as well as no guarantee of an optimal solution via these searches when considering complex & under-determined optimal problems.

Liu and McPhee also observed a gap in the body of research on type synthesis techniques: "The selection of the optimum topology among feasible mechanism structures for a specified task is still an open problem in the field of computer-aided mechanism design" (Liu and McPhee 2005). Liu and McPhee's research contributed to advancing the capability of software to perform automated type synthesis using genetic algorithms (GAs). Their program searches for optimal linkage topology with the assistance of evolutionary computation techniques[1] in an attempt to fully automate the type synthesis process from a numeric optimization approach.

More specifically, to automate this process of searching for optimal solutions, linkages are represented in matrix form. These researchers used a form notation called a link adjacency matrix (LAM), developed by (Tsai 2001). The image in Figure 13 shows the representation of a four-bar linkage in its standard structural representation, graph representation and adjacency matrix.

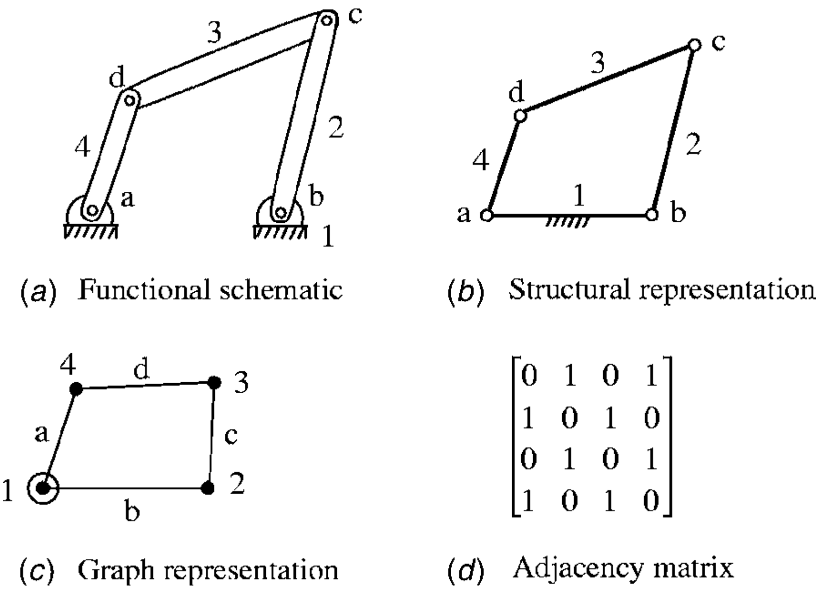

Figure 13: Four-Bar Linkage and Its Kinematic Representation (Liu and McPhee)

Although the graph representation used by Pucheta and Cardona (Pucheta and Cardona 2005) usually proves easier to translate into a structural representation than the LAM used

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[1] These techniques, specifically genetic algorithms, are explained in greater depth in Section 2.4.3.

[2] The Concept 0 mechanism did not tilt the skis in parallel. Therefore, according to the current PDS, it was an unsuitable solution

by Liu and McPhee (Liu and McPhee 2005), neither of the programs presented here possess the capability to automate this translation. While this research is a significant step towards effective type search automation, a disconnect remains between the practical, interactive requirements of mechanism designers and the programs designed to assist with linkage synthesis.

2.3 Dimensional Synthesis and Optimisation

The terms *dimensional synthesis* and *optimisation* are often interchanged in writings on linkage design since the process of synthesising link dimensions is performed concurrently with optimising the resultant path, motion or function. A generalised history of dimensional synthesis techniques is presented here based on Erdman's review article (Erdman 1995).

For many thousands of years, human history has been shaped by the design of new tools, mechanisms and linkage systems. Written history provides us with collections of illustrations and schematics of mechanisms that were primarily designed by mechanical intuition and trial-and-error. While the mechanism designer of today has more design helps at his disposal and can create more complex linkages more exactly and quickly, design is still and always will be something of an art as well as a science.

Prior to the 1950's, graphical, or sketching-based methods, were primarily used for linkage synthesis. Curve sketching, atlasing and basic systematic processes were introduced into the body of knowledge during the early twentieth century. Many of these advances produced design helps that are still used sixty years later.

In the years between 1950 and 2000, analytical & numerical optimisation methods were developed. Automation opened the door for the numerical and analytical representation of linkages and the efficient solution of the resulting complex equations.

In the present century, graphical and experimental methods will likely experience a resurgence in popularity as synthesis techniques may, perhaps, be integrated with some of the analytical methods developed in the latter half of the twentieth century. Software advances including automated iteration (direct search), computer vision and evolutionary programs make the unification of graphical, analytical and experimental methods a reality. An additional goal for the future will be to make advanced synthesis tools user-friendly. With the help of computers, the challenge of mechanism design problems "is not so much solving the governing nonlinear equations as much as it is formulating the problem in an intuitive manner" (Kinzel, Schmiedeler et al. 2006) These goals for future design tool development inspired the novel program concept, PSEO, introduced in Chapter 4 of this thesis.

The sections that follow will present methods for dimensional synthesis, beginning with analytical methods, then graphical methods and, finally, experimental methods. It is important to note that, for a single-loop linkage, determining the optimal dimensions of the links is a fairly straightforward task once the topology of the mechanism is specified. However, in most design situations, topology and dimensional characteristics are not identified in a discrete fashion. In addition, multi-loop linkages present a much more complex situation for link dimension determination. The relative merits of the synthesis methods presented in this section have been evaluated with these facts in mind.

2.3.1 Analytical Synthesis Methods

Graphical synthesis methods fell out of favour in the 1970's as analytical dimensional synthesis methods, including precision point synthesis and optimal synthesis, took precedence. During that period, the technological advancement and wider availability of computers directed the interest of mechanism researchers toward synthesis methods involving the solution of sets of equations (Fox and Gupta 1973). As computer technology has advanced further still, graphical methods have seen a resurgence in popularity and new kinds of experimental methods have been introduced (Reifschneider 2005; Shirazi 2005; Kinzel, Schmiedeler et al. 2006; Li and Tomovic 2009). However, analytical dimensional synthesis methods still remain relevant to the subject and continue to be widely taught in mechanism design courses. (Kimbrell 1991; Norton 1992; Molian 1997; Uicker, Pennock et al. 2003)

The analytical synthesis of mechanisms can be classified into two categories according to DaLio (2000). The first category deals with trying to "satisfy exactly a set of a necessarily few prescribed configurations" (Da Lio, Cossalter et al. 2000). It is known as the precision point approach.

The other category, called optimal synthesis, tries to "minimize the difference between specified and produced motions over the full range of operation". (Da Lio, Cossalter et al. 2000) D. Mundo (2006) provides a corroborating definition of these two types in his paper on the optimal synthesis of cam-linkage system. A brief review of these methods begins with a discussion of the precision point approach.

2.3.1.1 Precision Point Approach

The precision point approach, first developed by Freudenstein (Fox and Gupta 1973), allows the designer to synthesise a linkage that satisfies travel between specified precision points. In the literature (Hirschhorn 1962; Gold and Derby 1992; Norton 1992), most examples illustrating the usage of the precision point method involve the synthesis of a four-bar linkage with coupler to generate an approximate path. The precision point method does not take the intermediate positions of the coupler point, which are the points that are traced between the precision points, into account. Hence, this method is unsuitable for solving for a desired point path over the entire range of linkage motion. When a strong correlation between the actual and desired paths of travel is required using this method, a very large number of points must be identified, resulting in a very long and complex problem. In such cases, optimal synthesis is usually a more appropriate solution method.

At first glance, the usefulness of the precision point approach appears to be limited exclusively to problems requiring the satisfaction of precision points with a relatively simple linkage, such as a four-bar. However, it is also applicable to motion generation problems. An example from Norton (1992), illustrates the usage of this method for the purpose of motion generation.

It is first necessary to explain the process of obtaining vector loop equations, also referred to as loop-closure equations in Uicker et al. (2003), used in the analytical synthesis of linkages. Vector loop equations describe the relative positions of the links and the constraints provided by each of the joints between them. (Uicker, Pennock et al. 2003) To form a vector loop equation for a mechanism, the links are represented as position vectors. These vectors are connected at the joint positions in the linkage to form one or more closed loops (Norton 1992). Generally, linkages that contain more than five links will have links that form more than one closed loop (Doughty 1988). For these linkages, the process of constructing the vector loops is more complex, as is the process of solving the resulting equations. Synthesis methods for multi-loop linkages and the associated complexities are presented in the conclusion to this section and in Section 2.5.

A simple example of vector loop representation of a four-bar linkage is shown in Figure 14. The vectors, drawn from one of the ground joints, O_2, form one closed loop at point B.

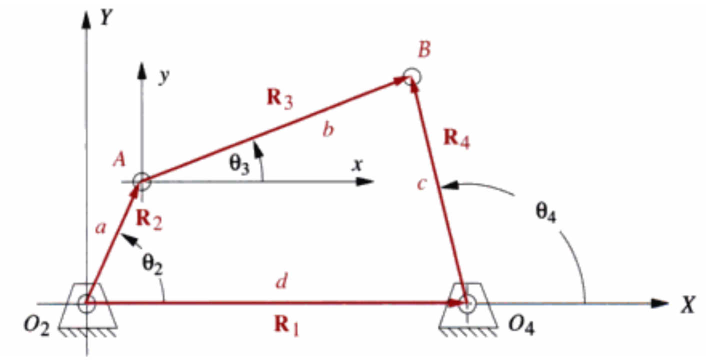


Figure 14: Position Vector Loop for a Four-Bar Linkage (Norton 1992)

From the vector loop constructed in Figure 14, Equation 1 can be obtained. Using polar or Cartesian notation, this equation can be expanded such that the orientations of vectors R2, R_3, and R_4 are expressed as angles with respect to the ground link, R_1.

Equation 1. Vector Loop Equation for a Four-Bar Linkage (Norton 1992)

$$R_2 + R_3 - R_4 - R_1 = 0$$

Using vector loop equations, Norton (1992) presents an analytical method for solving motion generation problem for three precision points and two coupler orientations. The design task presented by Norton stipulates that a four-bar linkage is the type of linkage chosen to satisfy the motion generation requirements (presumably arbitrarily), as it is necessary to specify the linkage type before performing analytical synthesis. Norton denotes the three precision points as P_1, P_2, and P_3. The subscripts indicate the order in which the coupler point must pass through the precision points. The angle of the coupler, α_2, is the angle between the first two precision positions and the angle, α_3, is between the first and third precision points. Figure 15 shows a four-bar linkage constructed in three positions that satisfy these requirements.

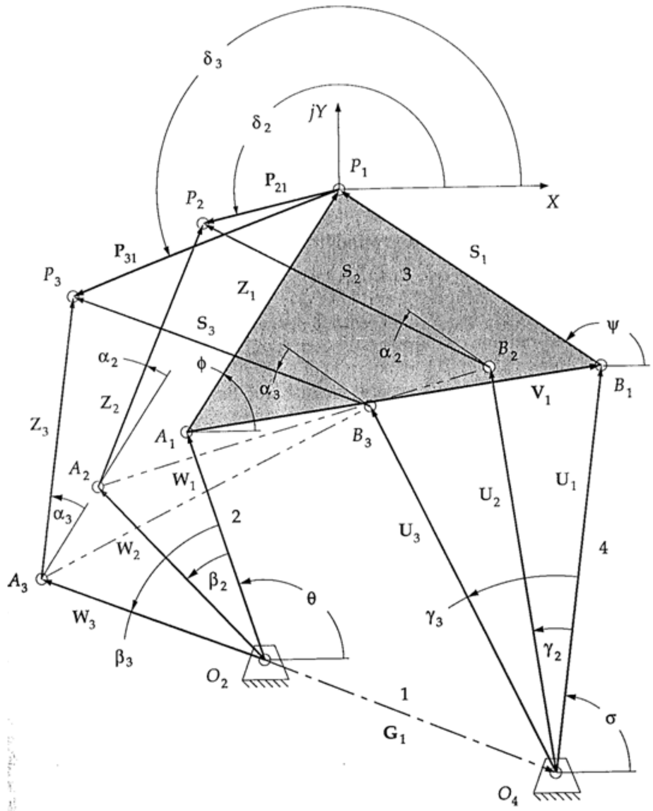


Figure 15: Analytical three-position synthesis (Norton 1992)

Two vector loop equations can be written to describe the four-bar linkage in two positions relative to the original position (P_1). By substituting complex number equivalents for the vectors, the loop equations can be expressed as Equation 2 and Equation 3. Equation 2 represents the linkage at precision point P_2 and Equation 3 represents the linkage at precision point P_3.

Equation 2. Loop Equation for Four-Bar at P_2 in Complex Number Notation (Norton 1992)

$$we^{j(\theta+\beta_2)} + ze^{j(\phi+\alpha_2)} - p_{21}e^{j\delta_2} - ze^{j\phi} - we^{j\theta} = 0$$

Equation 3. Loop Equation for Four-Bar at P_3 in Complex Number Notation (Norton 1992)

$$we^{j(\theta+\beta_3)} + ze^{j(\phi+\alpha_3)} - p_{31}e^{j\delta_3} - ze^{j\phi} - we^{j\theta} = 0$$

The loop equations would include twelve variables representing link lengths, their angular orientations and the precision point (coupler point) positions. However, only four of the twelve variables can be solved at once, so the other eight must be given or assumed values. The variables from the loop equations can be put into standard matrix form and solved with a program such as FOURBAR (Norton 1992) or any program capable of solving matrices. The solution yields link lengths for a four-bar mechanism that will exactly describe the specified precision points.

This presentation of the precision point method is simplistic, as the technique has been refined over decades to achieve error minimisation between the desired path of the coupler link and the resulting path of the synthesised coupler link. Research in this area is significant because the path of the coupler point between precision points is often important to control, but cannot always be conveniently expressed as a function.

Efforts to reduce the error between the desired point path and that of the solution path include precision point respacing (Fox and Gupta 1973) and the application of merit function evaluation (Gold and Derby 1992). The quasi-precision method developed by Mirth also aims to aid the designer in matching the shape of the path, motion or function plot to the design requirements in the absence of a well-defined functional requirement (Mirth 1993). While these methods are useful in addressing the shortcomings of the precision point method, they are calculation-intensive and can thus be difficult for the designer to apply.

The precision point approach and current research on the subject is important to introduce as part of a holistic review of mechanism synthesis methods because it has been widely studied and taught in mechanism synthesis courses, but it has limitations. First, the necessity to specify the linkage type before performing analytical synthesis is one of the most significant drawbacks to using this method. Designers in need of inspiration during the type synthesis phase of mechanism design require synthesis methods that readily provide information about the suitability of proposed solutions in fulfilling the design requirements. The time cost involved in creating the vector loop equations for each candidate solution and solving for the unknown variables renders the precision point method impractical for situations in which the type of linkage required is undefined, especially for complex and multi-loop synthesis problems.

These problems require many equations to solve. In such a design environment, it can be difficult to keep track of the design requirements and problem constraints. Also, as introduced in Chapter 1, some of the variables must be given guess values for under-defined problems, which can lead to impractical solutions.

Additionally, the designer cannot easily detect and account for constraint violations using the precision point method. Constraint violations must be checked as a completely separate operation when using the precision point technique (Fox and Gupta 1973). For this reason, it was not suitable for the synthesis of the Skiboard mechanism. The Skiboard design problem is bound by important constraints and requirements on the position and orientation of the output link throughout its range of motion. Attention to the entire range of motion is commonly necessary for the design of mechanisms involving human interface, making the precision point method unsuitable for many applications with such requirements.

Other considerations that would necessitate an alternative solution method were considered by DaLio (2000), which involve aspects other than geometry. These can be limits on forces, obstacles, tolerances, or limits on certain dimensions. The precision point approach does not deal with these requirements “and the only general method in this case seems to be a-posteriori analysis to verify whether some constraints are violated." (Da Lio, Cossalter et al. 2000)

2.3.1.2 Analytical Optimal Synthesis

The term optimal synthesis, which is widely referenced in literature, is the process of creating a mechanism that will best satisfy a given fitness function. Synthesis and function optimisation occur concurrently, hence the name. It would be fair to say that mechanism synthesis and the optimisation of the candidate configurations and dimensional combinations almost always occur together. However, the term *optimal synthesis* is used primarily to describe a solution process that involves numerical “search and experimentation” methods. (Da Lio 1997; Sancibrian, Viadero et al. 2004)

Numerical methods are employed for the purpose of determining the fitness of the proposed solutions with respect to a function or, in some cases, with respect to the satisfaction of a set or sets of constraints. There are many solution tools available to aide in the optimal synthesis process. A few of the most popular and recent methods are discussed in this section.

Optimal synthesis, compared to graphical or analytical methods, has become increasingly relevant as computers have improved their capabilities. This method is also the most suitable when continuous path generation is required. Additionally, it should be noted that the benefits of optimal synthesis also apply to situations requiring continuous function or motion generation. (Da Lio, Cossalter et al. 2000)

Optimal synthesis reduces the mechanism design problem to the minimisation of an objective function with equality and inequality constraints. There are variations of this type of synthesis, depending on how the objective function and constraint equations are formed and which function minimisation method is used. (Da Lio, Cossalter et al. 2000) DaLio (2000) presents a penalty-function-based analytical method that matches the motion of the linkage to the required motion. Their method ensures the exact satisfaction of constraints and the approximate satisfaction of functional requirements.

The analytical methods outlined in (Da Lio, Cossalter et al. 2000) are quite practical if the number and approximate configuration of links is known. The method provides the designer with optimal link dimensions for a mechanism that follows an approximate path or generates a prescribed function as nearly as possible. While concise compared to previously proposed methods, it is impractical for analysing a number of individual configurations due to the fact that the constraint equations are unique to each particular linkage configuration. Thus, it cannot evaluate across multiple configurations. A mechanism designer using optimal synthesis methods is limited to examining a small number of potential linkage configurations by the time cost of constructing new sets of equations for every new configuration.

2.3.2 Graphical Methods

Graphical synthesis methods involve sketching techniques that are used for dimensional synthesis of linkages. Before the personal computer became available and affordable, these sketching methods dominated the content of texts on the subject of mechanism synthesis (Tao 1964). L. Burmester pioneered graphical synthesis techniques in the 19th century with his presentation of sketching rules used to construct coupler curves for linkages with prescribed dimensions. These techniques are still used today, especially in situations involving simple linkages, to quickly predict the coupler point path and visualise the behaviour of a linkage. (Molian 1997)

L. Reifschneider (2005) presents a concise overview of synthesis methods, highlighting graphical techniques, and introduces bisection and overlay as the two most practically useful of these techniques. Bisection involves geometric construction to locate pivot points for a link. The locations of pivot points are determined based on two or three prescribed points along the coupler's path of travel. Figure 16, from (Li and Tomovic 2009), shows bisection construction lines in green, a coupler link in blue at its starting position and the same coupler link in dashed lines in two other prescribed positions.

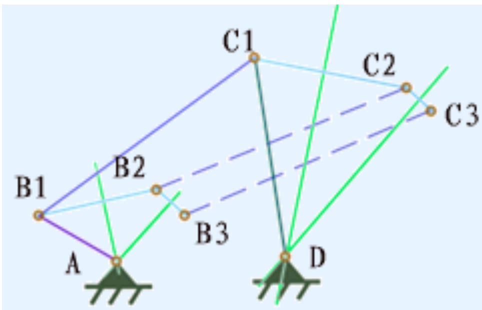


Figure 16: Four bar linkage synthesised by bisection

The overlay method is better-suited to solving function generation problems than bisection. When using this method, the designer redraws the crank (input link) and coupler (output link), each in several positions. The intersection of the lengths of these links is found for each set of positions and, from this information, the rest of the mechanism is synthesised. Figure 17 illustrates the overlay synthesis technique.

When presented with parametric software with sketching capabilities to aid in the design process, modern designers often choose to use graphical methods in order to stimulate creativity and obtain a working understanding of linkage kinematics. Thankfully for synthesis program designers, traditional pencil and paper sketching techniques cross over well to sketching packages in programs such as SOLIDEDGE, PRO/E, INVENTOR and SolidWorks, which is the software package used for this research. Kinzel is one of the most modern researchers to introduce a synthesis technique that employs some basic graphical methods within the sketching environment of parametric design software.

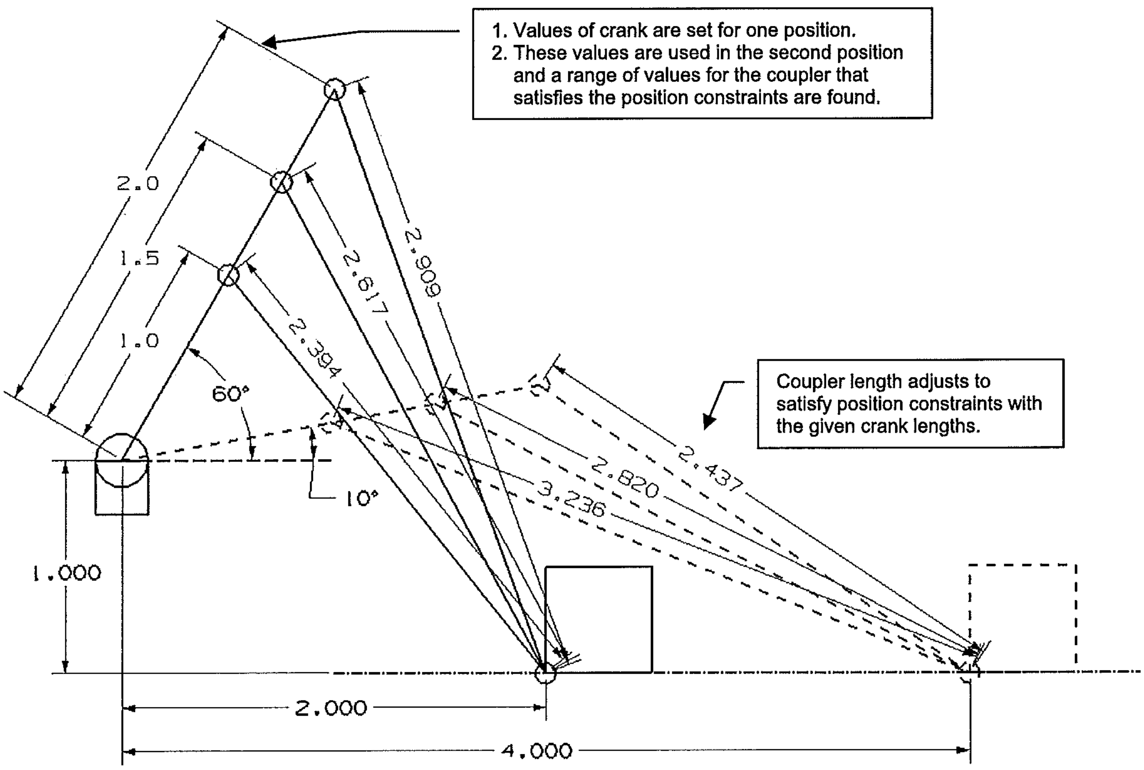


Figure 17: Overlay technique (Reifschneider 2005)

2.3.3 Experimental Methods

In the field of mechanism synthesis and optimisation, experimental methods have only very recently been formally recognised as viable design tools. Textbooks on the subject of mechanism design that have been published as recently as 2003 do not make reference to this type of synthesis method (Uicker, Pennock et al. 2003). While some research on experimental-type synthesis methods are included in literature reviews (Erdman 1995), they are not typically classified in their own discrete category.

In a lecture given at Purdue University on the kinematic synthesis of four-bar linkages (Li and Tomovic 2009), experimental methods were compared to analytical and graphical methods as follows:

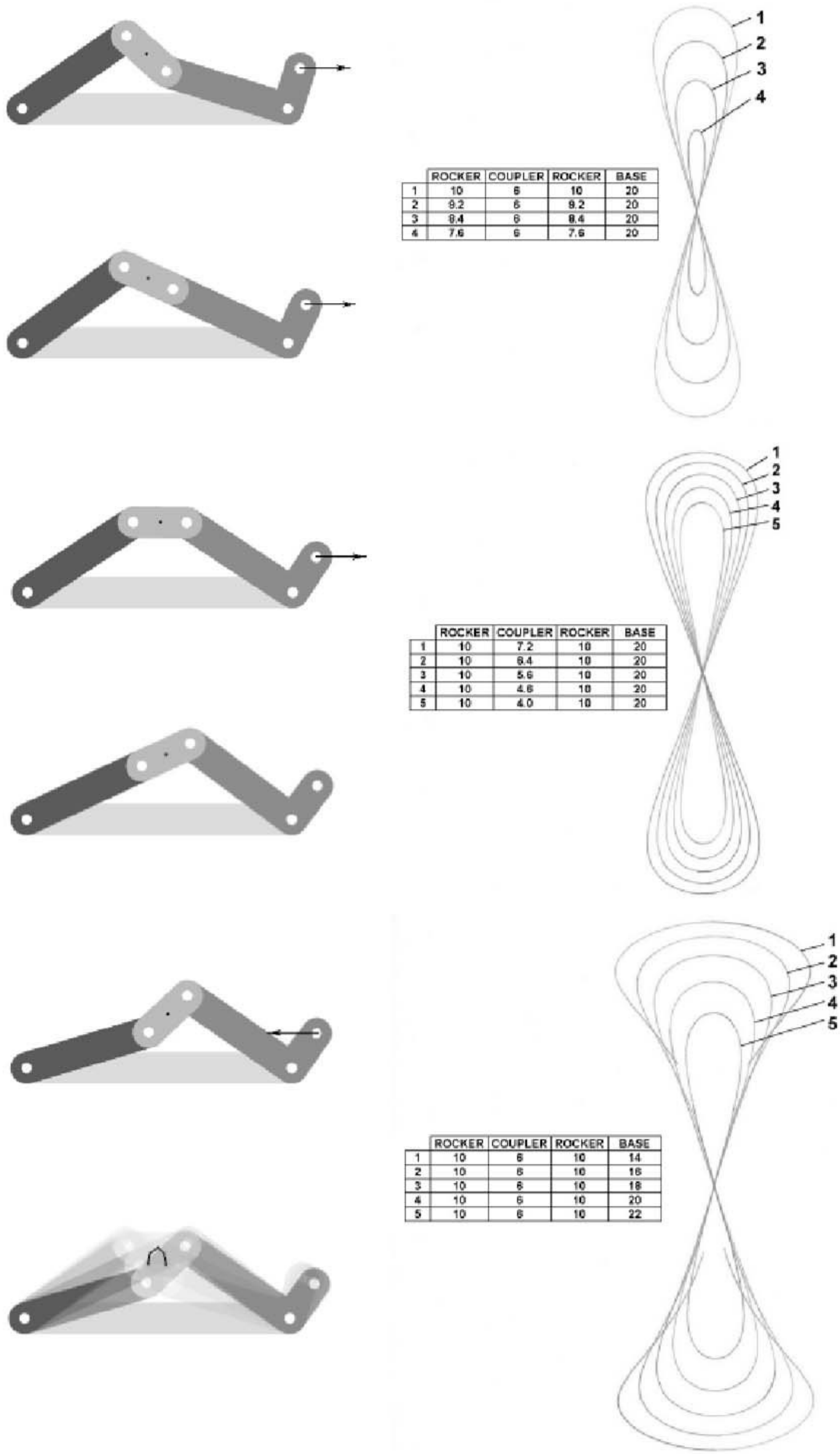
- Analytical: high precision
- Graphical: intuitive, simple, low precision
- Experimental: low precision

Without the assistance of CAD programs and metaheuristic algorithms, experimental methods would, indeed, provide very low precision solutions. However, it is becoming possible to use these computer-based tools to create an experimental environment that is capable of optimising mechanisms to a higher level of precision.

Experimental methods basically involve testing the behaviour of different configurations of a candidate mechanism in an effort to find the configuration that best satisfies the design requirements. Taking an experimental approach can be helpful to designers who have created a linkage configuration (or topology) and wish to test its behaviour over a range of dimensional combinations. Using a fitness function or set of fitness criteria, the designer can use a computer-based experimental setup to optimise the dimensions of the links.

As compared to analytical and graphical methods, experimental methods are an appealing option in some design situations for several reasons. First, the designer does not need to be familiar with the equations describing the kinematics of the linkage. This aspect is particularly helpful in situations involving multi-loop linkages, the kinematics of which are difficult to describe analytically. Second, experimental methods allow the designer to synthesise solutions more complex than four-bar or slider-crank linkages and test them directly. Hence, experimental methods are suggested as design tools for “black-box” optimisation problems, especially in instances where the design requirements are not concrete or there exists the desire to better understand the suitability of an existing solution concept.

There are examples in the literature of mechanism designers employing experimental methods of their own design who do not necessarily classify their methods as such. One notable example is a paper detailing the design of a micro air vehicle (Zbikowski, Galinkski et al. 2005). Two types of four-bar linkages were compared for their ability to create a figure eight coupler point path. Four-bar linkages were modelled using solid modelling software and different dimensional combinations for the links were tested. Atlases of various coupler point paths were obtained by tracing the path of the coupler point for each configuration. The most desirable configuration was chosen based on visual feedback provided to the designers by this experiment. Figure 18 shows samples of the experimental data obtained. The coupler curves appearing to the right of each table are labelled to correspond to combinations of link dimensions. The test setup and presentation of results concisely show the effects of different combinations of link dimensions on the size and shape of the coupler path.



	ROCKER	COUPLER	ROCKER	BASE
1	10	6	10	20
2	9.2	6	9.2	20
3	8.4	6	8.4	20
4	7.6	6	7.6	20

	ROCKER	COUPLER	ROCKER	BASE
1	10	7.2	10	20
2	10	6.4	10	20
3	10	5.6	10	20
4	10	4.8	10	20
5	10	4.0	10	20

	ROCKER	COUPLER	ROCKER	BASE
1	10	6	10	14
2	10	6	10	16
3	10	6	10	18
4	10	6	10	20
5	10	6	10	22

Figure 18: Experimental Design Employed by Zbikowski, et al.

Presumably, an experimental synthesis method was used due to its interactive nature and simplicity. In addition, the designers were faced with the challenge of having uncertain kinematic data that made analytically determining a "best motion envelope" difficult. Considering the lack of "reliable reference kinematics that could be used as input to a standard dimensional analysis", a designed experiment was thus used. (Zbikowski, Galinkski et al. 2005)

Overall, this example highlights the need for such methods that are interactive and lend themselves to solving problems with kinematically under-defined requirements, even if such problems involve the synthesis of mechanisms that are as simple and well-understood as a four-bar linkage. Computer software can be helpful in removing the designer a step from computational processes. However, it is important for the designer to be able to visualise solutions and be included in the design feedback loop, as iterations can inform the designer to produce better solutions.

Graphical synthesis is a quick, straightforward method for determining the dimensions of a linkage, but parameters cannot easily be manipulated to create new solutions. For this reason analytical or computer-based experimental methods are generally better suited to dimensional optimisation for under-constrained problems. Limitations to using experimental methods include long setup time required for defining the problem, constraints, etc.

Since the discussion of experimental synthesis methods plays an important role in this thesis, some of the underlying principles, metaheuristic methods and convention theories will be presented in more detail in the following section.

2.4 Experimental Synthesis Concepts and Metaheuristics

2.4.1 Metaheuristics

Metaheuristics (also termed *black-box optimisation*) allows a designer to test a candidate solution and assess its "goodness" based on a function or set of criteria. It is, in a sense, a type of computer-based experimental method and it is well-suited to problems that are not well-understood and cannot be readily modelled mathematically. Metaheuristics are a class of stochastic optimisation algorithms that employ at least some degree of randomness to search for an optimal solution to complex problems. (Luke 2009)

One fundamental difference between metaheuristics and designed experiments is that the user does not need to design an explicit or proven experimental method to use a metaheuristic algorithm. It is able to search a space, or range of variables, defined by the user and automatically iterate towards a solution. Another major advantage to using a metaheuristic algorithm is its ability to combine "hill-climbing" and random search to explore areas of the space in which favourable solutions are likely to lie. (Coley 1999)

Intelligent algorithms, such as genetic algorithms, are able to seek out global optima without much risk of getting caught in local optima. For this reason, solutions obtained via metaheuristic methods, especially with "guided" search algorithms like genetic algorithms, are usually quite robust. (Blum and Roli 2003) This robustness is due to the fact that an area of favourable solutions is likely to exist near the solution chosen as the "optimal".

The basic stages of metaheuristic solution search are as follows:

1. Algorithm initialisation – A solution value or set of values is either chosen randomly or defined by the user. (Capello and Mancuso 2003)

2. Evaluate objective function or other solution criteria
3. Solution convergence – The fitness or constraint satisfaction of the solution is determined. If the fitness is acceptable and the termination criteria are satisfied, the algorithm will stop. If it is unacceptable, the algorithm will continue to run. (Renner and Ekart 2003)
4. Variable tweak – A new value or set of values is created. Local search methods use hill-climbing (or, in the case of some, gradient ascent) to inform the choice of variable values. For guided algorithms such as genetic algorithms, a new population of solution values is created by the process of reproduction, crossover and mutation. (Renner and Ekart 2003)
5. Next iteration – The process is repeated starting from step 2.

The details of each of these steps vary depending on the metaheuristic method. Two of these methods, direct search and genetic algorithms will be briefly explained in the following subsections.

2.4.2 Local Search Methods

Local search methods, also called direct search methods, such as Hooke and Jeeve's and Powell's direct search method are used in a modern mechanism synthesis/optimisation program developed by Hicks and Medland (Hicks, Medland et al. 2006). An algorithm of this type starts the search for solutions from an initial solution, which is defined by the user. Iteratively, it replaces this solution with alternatives in the search space and moves towards values that provide better or more optimal solutions.

The hill-climbing approach used by local search algorithms is an easily-implemented way of automatically searching through a large range of possible variable solution values.

However, it has the drawback of being restricted to finding local minimal error solutions rather than global ones. This means the global optimal solution might be missed by using this method since it tends to search in a space that is near the initially defined solution value.

Hicks et al. (2006) acknowledge the disadvantage of being restricted to local minima, but rely on the interactive nature of their software to overcome this. If the user believes a more optimal solution might lie outside the initial search area, another search can be conducted using a different initial solution. If a more optimal solution cannot be found, the algorithm will return the solution found during the first run.

2.4.3 Genetic Algorithms

Genetic algorithms are a specific type of metaheuristic algorithm. They differ from search methods in that they approach the search for solutions based on evolutionary methods and intelligently "guide" the search process towards global rather than local solutions (Blum and Roli 2003). Liu and McPhee define genetic algorithms as "general-purpose stochastic optimization methods for finding global optima, especially suitable for poorly characterized solution spaces" (Liu and McPhee 2005).

Genetic algorithms are a type of computer-based evolutionary algorithm used to solve complex problems. The concept of modelling the mechanisms of natural adaptation with computer systems was first developed by John Holland of the University of Michigan in the 1970's. Since that time, genetic algorithms have been used by researchers in a myriad of fields, including mechanism design and robotics, to search through large numbers of possible solutions for a "best fit" solution. (Soni, Dado et al. 1988; Bain 1998; Cabrera, Simon et al. 2002; Lampinen 2003)

Genetic algorithms are modelled after the biological evolutionary process. The “rules” of this evolutionary process can be simply described as follows:

> *“Species evolve by means of random variation (via mutation, recombination, and other operators), followed by natural selection in which the fittest tend to survive and reproduce, thus propagating their genetic material to future generations.” (Mitchell 1996)*

Computer-based genetic algorithms work in the same fashion, where a “population” evolves until it consists of an optimal candidate solution or a set of optimal candidate solutions (as long as the end conditions of the program are not met first). New solutions are created from an initial population “via processes of selection, mutation and reproduction” (Heitkotter and Beasley 2001). Genetic algorithms have been explored in recent years as a tool for synthesizing and optimising linkage mechanisms to fulfil prescribed tasks because they are well-suited to combinatorial optimisation problems (Fang 1994). Detailed descriptions on the use of genetic algorithms for this purpose can be found in (Sedlaczek, Gaugele et al. 2005) and (Acharyya and Mandel 2009).

To effectively employ a genetic algorithm solution technique, it is usually necessary to establish a grammar, or mathematical construct, to express the relative configuration of the links and the joints (which are better understood in this case as *mobility restrictions*) between them. The graph grammar approach to mathematically characterising planar linkages was developed by Schmidt in 2000 who established the labelling conventions used in the field. Assur groups are another grammatical construct that can be applied to genetic algorithm techniques. (Hansen 1996)

The drawback to using graph grammar or Assur groups is that the kinematics of the mechanism are not discernable upon visual inspection of these mathematical expressions.

The designer is removed a step from the process and cannot easily check the progress or accuracy of the automated synthesis program in its search for solutions. While the foundation has been set for user-friendly GA-based synthesis programs to develop, this particular branch of this field of mechanism synthesis has not produced tools that are readily accessible enough to aid a designer in the early stages of the process.

The analysis stage of the iteration loop is also particularly challenging to automate, as matching the overall shape of the output function can be just as important as assessing path error in finding a suitable solution. To facilitate the proper selection of corresponding points on the two paths for comparison, a timing requirement can be imposed on the paths being analysed (Zhou and Cheung 2002). Additionally, as the author discovered during the course of this research, new shape comparison, or computer vision, tools can also be well-suited to this type of task. There is much in the way of future work in the area of automated synthesis with incorporated genetic algorithms.

2.5 Multi-Loop Linkages

The design task presented in this thesis, namely the design of the Skiboard, is a compound, multi-loop linkage synthesis problem. Most complex design tasks involving the satisfaction of more than one functional requirement will involve a multi-loop linkage solution. Figure 19 shows a six-bar and an eight-bar multi-loop linkage in graph representation from Lin and Chang (2003).

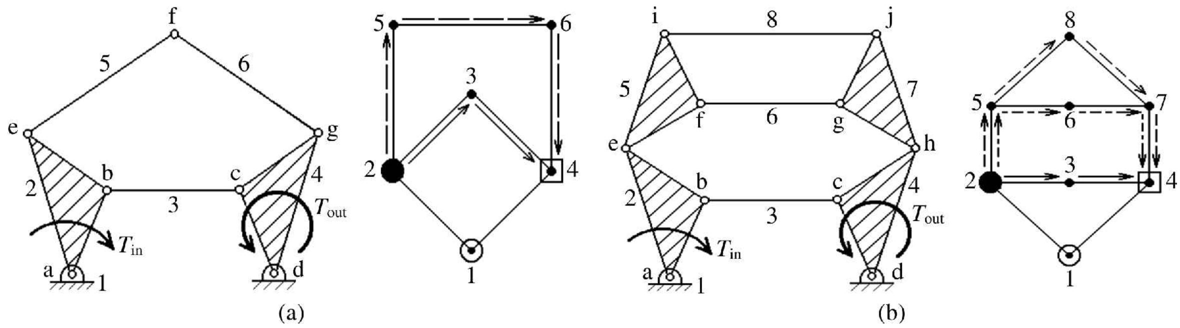


Figure 19: Multi-loop linkages in graph representation

In graph representation, links are denoted by vertices and joints by edges. This notation makes the multiple closed loops contained in these linkages clearly visible.

Although some six-bar linkages can be single loop, most linkages with more than four links contain at least two closed loops (Doughty 1988). The closed loops can be represented by loop equations, as shown in Section 2.3.1.1, which means that linkages with more than one loop produce analytically complex problems, especially when analysing for link velocity and acceleration. Apart from added complexity, however, the analysis of multi-loop linkages requires the use of the same types of tools as simpler linkages.

Where synthesis is concerned, multi-loop problems, especially those involving multiple functional requirements, are difficult to solve. The majority of the literature on the subject of multi-loop linkages has to do with robotics (Shen, Ting et al. 2000; Porta, Ros et al. 2006; Han and Rudolph 2009). While these publications include information on the analysis and optimisation of these linkages, little insight into the synthesis process is given. For these problems, it is assumed that designer creativity plays an important role since most synthesis software tools do not allow for the stipulation of two or more separate functional requirements.

It can be helpful to the designer to segment the design space based on functional requirements and use sketching tools to brainstorm solutions. This type of segmentation was used to construct the Skiboard linkage concepts. Synthesis and optimisation of multi-loop linkages are discussed further in Chapter 3 and Chapter 4.

2.6 Summary

There is a consensus throughout literature that the overall process of mechanism synthesis is as much an art as it is a science. When it comes to mechanism synthesis, the ability of a designer to conceive of great solutions and influence the design process cannot be overestimated. Since most mechanism design does not take place independent of the designer's creativity, mechanism synthesis, analysis and optimisation tools are most beneficial to the process if they are flexible and interactive to the degree that the designer's inspiration is allowed to influence the results throughout the design process.

Mechanism design is not an exact science that can be assigned a global numerical procedure. Rather, numerical analysis becomes a key part of a multi-step, iterative design process. The process being proposed in this thesis is a compilation of methods proposed by other researchers and novel experimental methods designed specifically for this application.

Chapter 3.

Solid Model Atlas Creation (SMAC) and Experimental Synthesis

This chapter introduces computer-based concept generation and experimentation techniques created for this thesis and to assist mechanism designers who are faced with complex, under-constrained synthesis problems. They are intended for use during the type synthesis design phase, when the designer is choosing a linkage configuration and approximate link dimensions to satisfy given design requirements. They are also applicable during dimensional synthesis, when the user is seeking optimal link dimensions.

Depending upon the simplicity of the linkage, analytical methods as explained in Chapter 2 may be practical for dimensional synthesis and produce more accurate results than the experimental methods presented in this chapter. However, for most complex problems involving compound and/or multi-loop linkages like the Skiboard mechanism, experimental synthesis and optimisation methods are preferable. One significant design advantage is that the linkage kinematics do not need to be fully understood or rigorously calculated to use experimental techniques.

Two experimental linkage synthesis techniques are discussed in this thesis in the order of their development. The first, which will be referred to as Solid Model Atlas Creation (SMAC), was developed for and used throughout the type and dimensional synthesis phases of designing the Skiboard. It is discussed and explained in detail in this chapter.

The second technique, called PSEO, is a more thoroughly automated type and dimensional synthesis program. The concept for PSEO developed through literature survey and through observing the limitations of SMAC. As its development into a fully functioning software package will require more time and programming expertise, it is presented as a concept in Chapter 4.

The primary user interface environment for both SMAC and PSEO is the SolidWorks modelling environment. This environment allows for 3D modelling with associated kinematic and kinetic analysis, as utilized by SMAC, and 2D parametric modelling with kinematic analysis, as utilized by PSEO. Changes to a model can be carried out automatically by writing code in Visual Basic for Applications (VBA). VBA is highly compatible with SolidWorks and with other user-friendly data storage and analysis software such as Microsoft Excel.

The fundamental concept underlying the SMAC program is a method of systematic experimentation and feedback analysis called designed experiments. The design of experiments is a field in itself, based in statistics and numerical analysis. A brief overview of the basic concepts is presented in Section 3.1 to set the stage for an explanation of the program.

The SMAC program was used several times for the testing and optimisation of candidate Skiboard linkages. However, for the purpose of demonstrating the program's setup and functionality, most screenshots are taken from experiments involving Concept 3 and Concept 6, as the individual links of these designs are easily seen in screenshots.

3.1 Design of Experiments

Design of Experiments (DOX, or DOE according to some authors) is a collection of statistical methods used to analyse the interactions between factors (input variables) and the sensitivity of output variables to changes in these factors. It is relevant across a wide range of scientific fields, as the primary goal in scientific research is generally to show the statistical significance of a particular factor's effect on a dependent variable of interest. It has only recently become relevant in the field of mechanism design, where it would never have been a realistic option for use before computer automation.

DOX can be applied in the field of mechanism design by creating a virtual test setup using a 2D or 3D model of a linkage. The designer can quickly and easily observe the results of different combinations of link dimensions and how changing factors can make a design more or less suitable as a solution. In this way, DOX can be used during the initial sizing and type synthesis portion of the linkage design process.

Some researchers have sought to extend the use of DOX past dimensional synthesis into type synthesis. This, however, is a large and complex undertaking since the number of variables involved in attempting every type/dimension combination is nearly infinite. With the help of user constraints and powerful technology, programs that delve into the realm of automated experimental type synthesis might someday exist. However, for the time and for the purposes of this thesis, the influence of DOX is limited to dimensional synthesis.

3.1.1.1 Factorial Designs

The most intuitive approach to initially performing a study of factors would be to try all possible combinations of values, or use what is called a full factorial design. This technique would, of course, be expensive and impossible in most cases. Even if only the high/low combinations of all the input factors is tested, the number of experiments, or runs, required to complete such a study increases geometrically with the number of variables. Table 1 illustrates the way adding just one or two variables to a two-level full factorial experiment can greatly increase the number of runs required. (Croarkin and Tobias 2007)

Table 3: Number of Runs for Full Factorial Designs

Number of Factors	Number of Runs
2	4
3	8
4	16
5	32
6	64
7	128

It is also important to note that only testing high and low values, when it comes to link dimensions in a given configuration, is insufficient for determining the behaviour of the mechanism across a range of possible configurations. A simple four-bar linkage can easily explain the need to test mid-range values for link dimensions. A page from the Hrones and Nelson Atlas (1951), shown in Figure 9, demonstrates the way in which even small dimensional changes can significantly affect the coupler curve produced by a linkage.

One way to minimise the number of runs required for an experiment and allow for the testing of mid-range values as well as high and low values is to conduct a fractional factorial experiment. For this kind of experiment, only an adequately chosen fraction of the treatment combinations required for the complete factorial experiment is selected. Fractional factorials ‘sacrifice’ some interaction effects so that main effects may still be computed correctly (Montgomery 1997). When running an experiment with many variables of wide-ranging values, this type of experiment can be used effectively to narrow down the range of possible solution values.

There are several types of fractional factorial experiments in literature that can be applied to virtually as well as physically conducted engineering experiments. The one of most interest for the application of testing link length variables, the Taguchi orthogonal array, is presented in Figure 20. It allows for the testing of three value levels of each variable, a high, medium and low value. In Figure 20, the number 1 represents a low test value, 2 represents a mid-range value and 3 signifies a high test value. (Croarkin and Tobias 2007)

Run	X1	X2	X3	X4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Figure 20: Three-Level Fractional Factorial Experiment for Four Variables

The array presented in Figure 20 is used for an experiment involving four variables and is shown as an example only. Literature contains arrays for experiments involving more than four variables (Montgomery 1997). This type of experimental design can provide the designer with critical information about variable sensitivity in a relatively few number of runs. One drawback to using this method for experimentation is that the interaction effects of the variables with each other are difficult to determine.

The principles of fractional factorial experimental design inspired the method of testing the Skiboard in SMAC by influencing the choice of the variable link dimensions to be tested. This topic is discussed in more detail in Section 3.2.1.2.

3.1.1.2 DOX and SMAC

Design of Experiments was studied in search of an efficient method for assessing the suitability of different Skiboard designs and determining the optimal dimensional combination for a design. In particular, DOX was enlisted to assist with the following:

1. Determining which variables are most significant in changing the output motion
2. Finding a way to test the design space for favourable dimension combinations without testing every combination

The interactive virtual environment provided by SolidWorks lent itself well to designing experiments with concept models in a systematic fashion.

3.2 SMAC Program Structure

SMAC is reflective of similar ad hoc experimental processes that are developed by mechanism designers during the synthesis of complex linkages. A similar process concurrently developed for the design of a micro air vehicle is found in (Zbikowski, Galinkski et al. 2005). The software in this work differs from SMAC in that it is not presented as an automated experimental setup. It was also an ad-hoc, one-off development that was not intended as a design tool first.

It is important to note that Zbikowski's design task involved the synthesis of a four-bar mechanism, a widely useful and very well-understood type of linkage. There are many analytically based programs and tools in existence to aide designers of four-bar linkages. However, none suited these particular designer, who were faced with an under-constrained design problem and under-defined task requirements.

The structure of the synthesis tool required for Zbikowski's application, and for the Skiboard task, follows the simple feedback loop presented in Figure 9. It is important to note, however, that the "synthesis engine" referred to in the flow chart is, in this case the designer. Creative solutions are suggested by the designer, different combinations of link dimensions produce a range of mechanisms and the performance of each of these solutions is simulated and reported back to the designer.

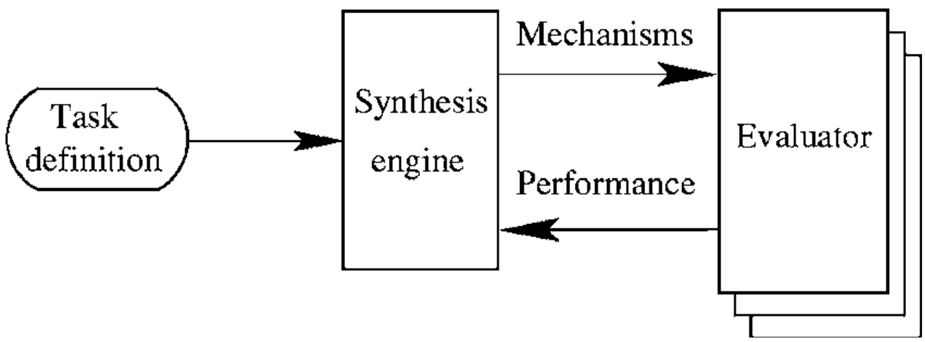


Figure 21: Distributed Architecture for Mechanism Synthesis (Liu and McPhee 2005)

3.2.1 SMAC Software

SMAC uses SolidWorks as the 3D modelling interface and testing environment. Excel is used as a commercially, readily accessible atlas builder. Finally, Visual Basic for Applications (VBA) provides the link between these two programs. Programs with similar capabilities and compatibility could be used in place of these.

Using the SMAC software, the designer (or user) is able to create a 3D solid model assembly of a "candidate", or possible best solution, linkage to a path-, motion- or function-generation problem. The tool then allows the user to experiment with the behaviour of the linkage throughout its range of motion. The dimensions of the links can be changed and the new behaviour tested to help determine whether or not that particular linkage configuration has the potential to satisfy the functional requirements. This task can iterate automatically until an entire experiment has been completed.

SMAC offers a simple and easily-modifiable method to perform early-stage dimensional synthesis and to inform the designer in choosing an appropriate linkage topology to fulfil the required task. Its main strength lies in its ability to reference a solid model. Since an assembly model contains information about constraints, it is unnecessary for the user to program these constraints into the synthesis/optimisation software. SMAC is also capable of creating atlases for different link topologies that are unique to the user's design process and lend themselves to visual inspection.

3.2.1.1 Part 1: Solid Modelling - SolidWorks

The first step in using the SMAC experimentation method is to create a 3D model of a linkage mechanism as a virtual assembly of parts in SolidWorks. The constraints between each link are defined within the SolidWorks design environment by assigning mates. For example, a link can be constrained at one end to rotate about a pin by assigning a concentric mate to the hole in the link and the pin.

At this stage, it is crucial for the designer to carefully constrain the model within SolidWorks, as a poorly constrained assembly will either produce errors or behave in a manner that is unrealistic. It is also important to give unique and meaningful names to each of the parts in the model. The names are referenced by Visual Basic to change the associated dimensions during the experiment.

Figure 22 shows the Concept 3 mechanism in the SolidWorks 3D modelling environment. The names of the links are shown in the feature manager along the left-hand side of the screen. The names of the dimensions such as D1, D2, etc. , which are also referenced by VBA when changing the variables, are shown in the image as well.

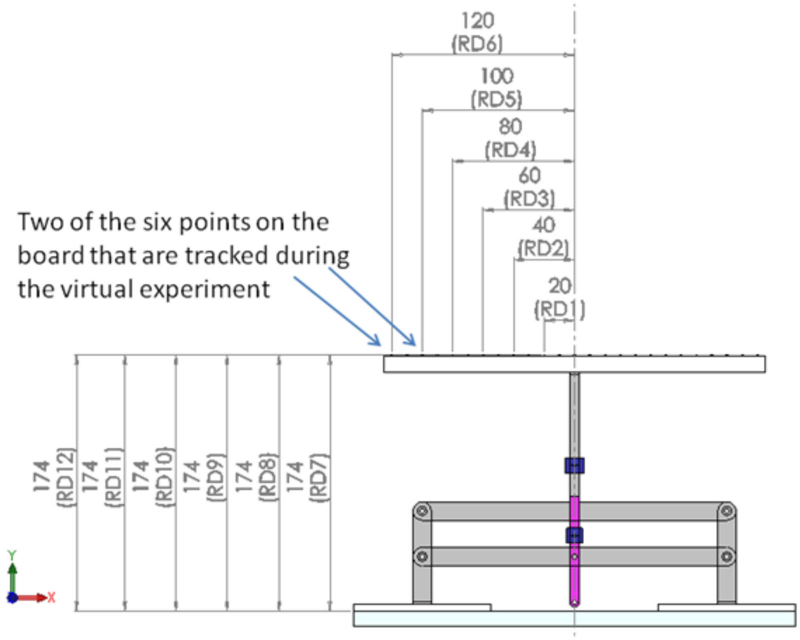


Figure 22: Concept 3 Solid Model

A solid model like the one displayed in Figure 22 can be altered dimensionally in any way using VBA. Additionally, the position coordinates of any point on any link can be known and recorded using VBA. These capabilities were used during virtual experimentation and are explained in greater detail in the sections that follow.

3.2.1.2 Part 2: Excel

An Excel spreadsheet is created by the designer to specify the dimensional combinations tested. Each set of link dimensions comprises a discrete configuration. Figure 23 shows a portion of the configurations defined for an experiment with the solid model for the Concept 3 mechanism. High-, low- and mid-range test values were tested for the two variables that, in prior experiments, appeared to be the most sensitive.

While fractional factorial design inspired the choosing of variable values for testing, it could not be followed explicitly due to rebuild errors in SolidWorks. Certain dimensional combinations resulted in infeasible or erroneously rebuilt models. This tendency was especially prevalent when the combination of high value variables with low value variables occurred and the model could not satisfy its constraints by reassembling all of the specified mates.

1	Component1	Component2	Component3	Component4	Component5	*Sheet No.*		
2	b	l	t	r	v			
3	6	30	30	10	80	*2*	*r*	10, 15, 20
4	6	30	30	15	80	*3*	*t*	30, 40, 50
5	6	30	30	20	80	*4*	*l*	30, 40
6	6	30	40	10	80	*5*	*b*	6, 12
7	6	30	40	15	80	*6*	*v*	80, 140
8	6	30	40	20	80	*7*	ski sep: 20mm	
9	6	30	50	10	80	*8*		
10	6	30	50	15	80	*9*	r	radius
11	6	30	50	20	80	*10*	t	top slider
12	6	40	30	10	80	*11*	l	leg height
13	6	40	30	15	80	*12*	b	bottom slider
14	6	40	30	20	80	*13*	v	vertical link
15	6	40	40	10	80	*14*		
16	6	40	40	15	80	*15*		
17	6	40	40	20	80	*16*		
18	6	40	50	10	80	*17*		
19	6	40	50	15	80	*18*		
20	6	40	50	20	80	*19*		
21	6	30	30	10	140	*20*		
22	6	30	30	15	140	*21*		
23	6	30	30	20	140	*22*		
24	6	30	40	10	140	*23*		
25	6	30	40	15	140	*24*		
26	6	30	40	20	140	*25*		
27	6	30	50	10	140	*26*		

Figure 23: Link Dimensions for Each Configuration - Sample Screenshot

Rebuild errors during an experiment produced one of two possible situations. In the first circumstance, the program (or experiment) would stop and need to be restarted. The second, and more problematic, situation involved the rebuilding of the linkage in an upside-down configuration.

Once an upside-down configuration is created, the remaining experimental runs are executed using a model that has been rebuilt in this flawed configuration. It is sometimes difficult to notice that this type of error has occurred when looking at the results as output paths. Therefore, as an error-checking help, the VBA program written for SMAC was expanded through the course of this research to include an image of the model in each configurations with the rest of the results. The results are discussed in Section 3.2.4.

To avoid rebuild errors, the high and low, or extreme, values for some of the variables had to be manually adjusted by trial and error. The time-consuming nature of working around the rebuild errors in the 3D modelling environment inspired the concept for a 2D sketching-based experimental program, discussed in Chapter 4.

3.2.1.3 Part 3: VBA Automation

A Visual Basic code portion of SMAC controls the iterations of the designed experiment. It changes the variable values in SolidWorks based on the data contained in Excel and reports results from the model simulation back to Excel as point paths. In the case of the experiments for the Skiboard, the code was set up to record the position of points along the board throughout a range of ski angulation. These points are shown in Figure 22.

Each experiment on a concept is performed, via VBA, by moving the Skiboard model throughout its range of motion, or ski angulation. Motion is controlled by changing the angle between the ski and the ground, as shown on the Concept 6 model in Figure 24.

The portion of the code controlling the feedback of the point position information to Excel is contained in its entirety in Appendix C. The file extensions, link names and dimension names has to be changed each time the code is used to test a new concept, but the remaining commands remained essentially the same. The model data that is fed back to the spreadsheet can be used to create plots of path, motion, function or other relevant relationships.

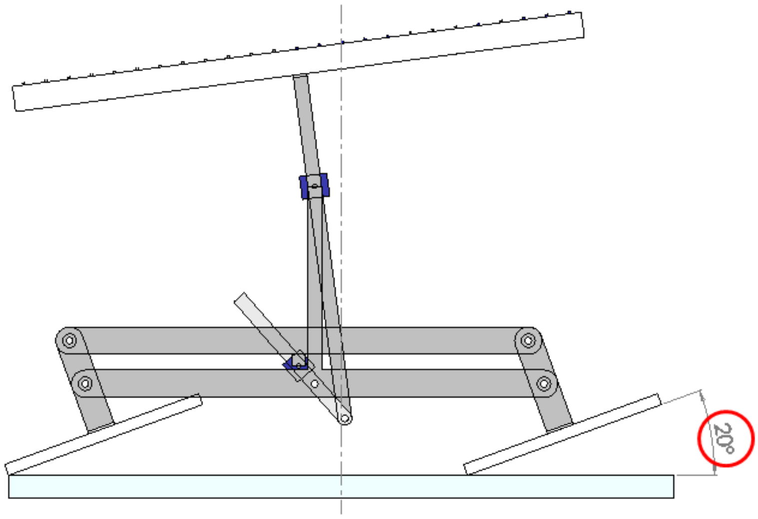


Figure 24: Concept 6 with Motion Control Dimension

When a configuration has been run through its range of motion, the code resets the model to its starting position (zero degrees of ski tilt, in this case). It then changes the dimensions of the links in the model according to the information contained in the spreadsheet. All configurations are run through until the end of the dimension sets in the spreadsheet or until an infeasible rebuild is encountered.

3.2.2 SMAC Atlasing

SMAC is capable of creating atlases of the designer's linkage and its motion characteristics for different combinations of link dimensions. The appearance of these atlases is similar to those created by Hrones and Nelson (Hrones and Nelson 1951) discussed in Chapter 2. Hence, the tool, uniquely, keeps a design and documentation history. For designers deeply involved in a complex mechanism synthesis task, keeping a design history can be useful in avoiding the repetition of solution proposals. None of the existing synthesis programs reviewed for this thesis possessed visual atlasing capabilities.

A novel approach to mechanism atlasing was used to assess the suitability different configurations of Skiboard linkages. The results are discussed in Section 3.2.4. For each configuration, the following information was exported to Word to create an easily examined atlas document:

1. An image of the solid model from SolidWorks
2. A plot showing the paths of the specified points along the board
3. A plot of the resulting characteristic curve (explained in detail in Chapter 5)
4. A chart showing the variable values comprising the configuration

The interactive nature of the SMAC tool lets the designer use the atlased results of the experiments to provide further insight and direction to the process. Thus, it allows the designer to maximise what they do best (ideate) and the computer what it does best (compute and optimise).

3.2.3 Experimental Iterations

For initial experimental iterations, the program was stopped short of creating an atlas because the purpose of experimentation, at first, is to assess a wide range of variable values and hone subsequent iterations to optimise these values. Thus, the atlasing capabilities of SMAC were used more for optimisation than for initial link sizing. For the first experiments that tested a wide range of variable values, an automated criteria-checking routine was written into the Excel portion of the program.

A cursory sensitivity analysis of each set of results was performed to determine which dimensional combinations were creating linkages that produced desirable outcomes. Excel was set up to test the results according to the following criteria, which are explained in greater detail in Chapter 5:

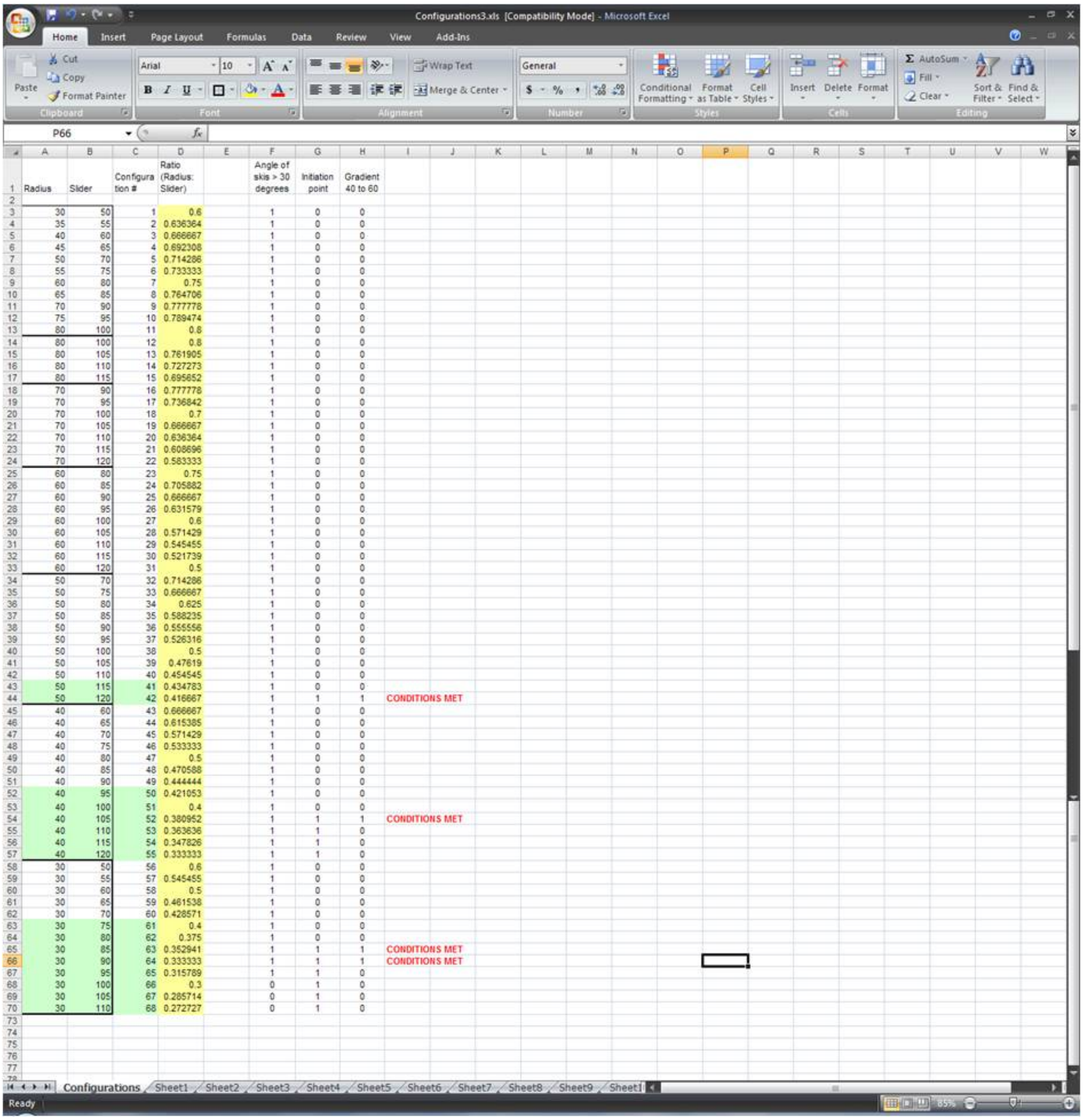
1. Maximum ski angle with respect to board angle

2. The point along the board that initiates ski movement (referred to as the initiation point)
3. The presence of board point path involute curves, confirmed by checking for minima in the point paths

The three test conditions are shown in columns in Figure 25. If a linkage configuration satisfies these three criteria, the red text "Conditions Met" appears in the row corresponding to the satisfactory configuration. Four of the configurations for the experiment shown meet the test criteria.

Using the method shown, sensitivities of the linkage behaviour to certain variable values became apparent. In the case of the experiment conducted to produce Figure 25, favourable results were produced with a low radius (variable 1) value and a relatively high slider (variable 2) value. Additionally, the data shows that the ratio of these two variables is optimally less than 0.42.

In variable ranges that demonstrated more favourable results, finer dimensional variations were tested, iteration by iteration, until optimum values are found. From the data in Figure 25, for example, more a smaller range of test values was chosen for the next experiment with a concentration on low radius values and high slider values.



Radius	Slider	Configuration #	Ratio (Radius: Slider)	Angle of skis > 30 degrees	Initiation point	Gradient 40 to 60	
30	50	1	0.6	1	0	0	
35	55	2	0.636364	1	0	0	
40	60	3	0.666667	1	0	0	
45	65	4	0.692308	1	0	0	
50	70	5	0.714286	1	0	0	
55	75	6	0.733333	1	0	0	
60	80	7	0.75	1	0	0	
65	85	8	0.764706	1	0	0	
70	90	9	0.777778	1	0	0	
75	95	10	0.789474	1	0	0	
80	100	11	0.8	1	0	0	
80	100	12	0.8	1	0	0	
80	105	13	0.761905	1	0	0	
80	110	14	0.727273	1	0	0	
80	115	15	0.695652	1	0	0	
70	90	16	0.777778	1	0	0	
70	95	17	0.736842	1	0	0	
70	100	18	0.7	1	0	0	
70	105	19	0.666667	1	0	0	
70	110	20	0.636364	1	0	0	
70	115	21	0.608696	1	0	0	
70	120	22	0.583333	1	0	0	
60	80	23	0.75	1	0	0	
60	85	24	0.705882	1	0	0	
60	90	25	0.666667	1	0	0	
60	95	26	0.631579	1	0	0	
60	100	27	0.6	1	0	0	
60	105	28	0.571429	1	0	0	
60	110	29	0.545455	1	0	0	
60	115	30	0.521739	1	0	0	
60	120	31	0.5	1	0	0	
50	70	32	0.714286	1	0	0	
50	75	33	0.666667	1	0	0	
50	80	34	0.625	1	0	0	
50	85	35	0.588235	1	0	0	
50	90	36	0.555556	1	0	0	
50	95	37	0.526316	1	0	0	
50	100	38	0.5	1	0	0	
50	105	39	0.47619	1	0	0	
50	110	40	0.454545	1	0	0	
50	115	41	0.434783	1	0	0	
50	120	42	0.416667	1	1	1	CONDITIONS MET
40	60	43	0.666667	1	0	0	
40	65	44	0.615385	1	0	0	
40	70	45	0.571429	1	0	0	
40	75	46	0.533333	1	0	0	
40	80	47	0.5	1	0	0	
40	85	48	0.470588	1	0	0	
40	90	49	0.444444	1	0	0	
40	95	50	0.421053	1	0	0	
40	100	51	0.4	1	0	0	
40	105	52	0.380952	1	1	1	CONDITIONS MET
40	110	53	0.363636	1	1	0	
40	115	54	0.347826	1	1	0	
40	120	55	0.333333	1	1	0	
30	50	56	0.6	1	0	0	
30	55	57	0.545455	1	0	0	
30	60	58	0.5	1	0	0	
30	65	59	0.461538	1	0	0	
30	70	60	0.428571	1	0	0	
30	75	61	0.4	1	0	0	
30	80	62	0.375	1	0	0	
30	85	63	0.352941	1	1	1	CONDITIONS MET
30	90	64	0.333333	1	1	1	CONDITIONS MET
30	95	65	0.315789	1	1	0	
30	100	66	0.3	0	1	0	
30	105	67	0.285714	0	1	0	
30	110	68	0.272727	0	1	0	

Figure 25: Screenshot of Analysis Table

3.2.4 Results

The VBA code can be easily modified to display any set of results that the user may find helpful in analysing the suitability of a set of solutions. Plots showing any point path traced by any link in the assembly can be created in Excel and exported to Word to compile an atlas of meaningful results. Appendix D provides an example of the kind of results available to the designer with SMAC.

A screenshot is included in the results showing the linkage at the end of its range of experimental motion. As mentioned previously, it was added to the atlas as an error check to prevent the usage of data obtained from an incorrect or upside-down configuration. Plots created by the user in Excel along with a chart showing the dimensions used for the experiment appear below the screenshot of the model.

3.3 Kinetic Analysis and SMAC Validation

A kinetic test was carried out, not only to confirm the results provided by SMAC, but to test the force response of the linkage configuration. SolidWorks includes a kinetic analysis package called COSMOSMotion. This analysis package is easily applied to existing solid model assemblies by assigning force- and friction-related constraints to the links.

3.3.1 Kinetic Testing Assumptions

Technically, the Skiboard could be classified as a kinematic chain rather than a linkage due to the fact that none of the links are fixed to the ground. However, for synthesis and analysis purposes it has been treated as a linkage due to the fact that the snow surface acts as an effective ground link between the skis. The Skiboard will move relative to the ground in practice and the terrain will change, but for synthesis and analysis purposes it has been assumed that the “ground” is a solid, fixed plane.

Basic force analysis has also been carried out under this assumption because it is nearly impossible to predict the force distribution between the bottom of the skis and the snow at any given time due to widely varying riding conditions and weight distribution of the rider. An attempt to model these conditions would not significantly contribute to the kinematic synthesis of the snowboard linkage due to the wide range of possibilities. More generally, this assumption should always hold unless the rider is airborne, at which time linkage kinematics do not influence performance.

Another assumption that was made for testing purposes concerns the definition of the input and output links. Seen from a rider's perspective, the input and output links are one and the same. The board beneath the rider, along with the fixed support link attached to the bottom side, could be considered the input link since it is the link in contact with the rider that directly transfers the applied force to the other links in the mechanism. From this perspective, it is also the output link because it gradually follows a path and series of orientation positions that influence the rider's stability and the quality of his or her riding experience. Thus it is the behaviour of this link, along with the relationship between its orientation and the orientation of the skis, that matters to the rider.

3.3.2 COSMOSMotion Test

A COSMOSMotion experiment was carried out for every concept that showed potential to satisfy the design requirements. The COSMOSMotion image for Concept 3 is shown in Figure 26. The purple arrow represents the applied force, or simulated rider force. The paths of selected points along the board are traced out by the red pencil icons.

The raised circular features along the width of the board were created as "point force" locations. A force applied to a model in the COSMOSMotion environment is distributed equally over the identified surface, so concentrating an applied force at a specific location (to represent the applied force as a resolved force) must be done by creating a unique feature. One of these raised features was placed every 10 mm along the board so that the simulation could test the response of the Skiboard to shifts in the rider's resultant force location along the board.

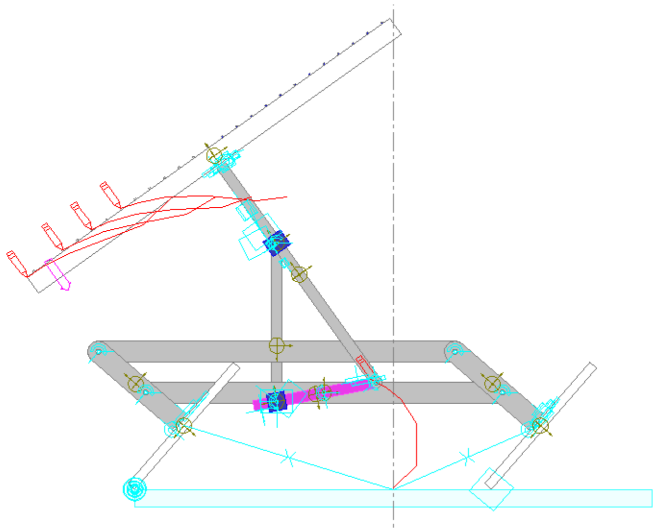


Figure 26: COSMOSMotion Test - Concept 3

The COSMOSMotion tests validated the results produced by SMAC for every concept tested. Sample validation images are contained in Figure 27. The image on the left was produced by SMAC and shows the paths of selected points along the board. The image on the right is a solid model image from COSMOSMotion showing the same configurations producing the same point paths.

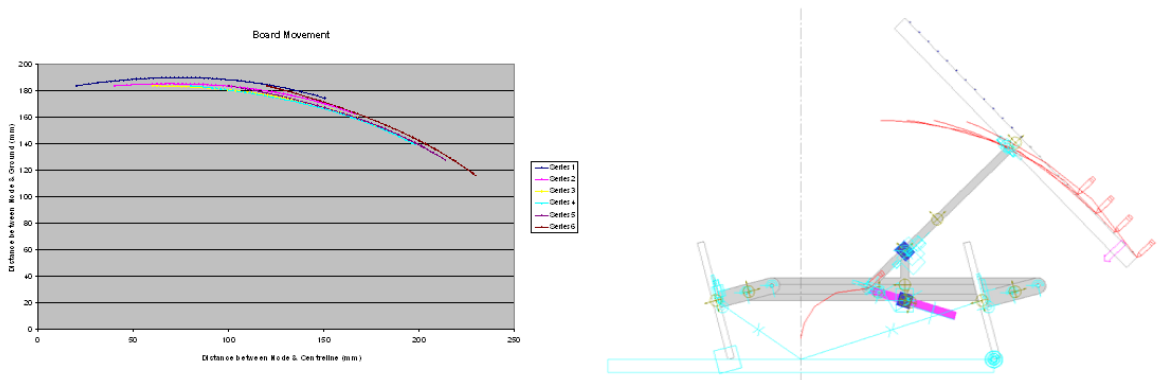


Figure 27: SMAC/COSMOSMotion Comparison

COSMOSMotion also introduced force considerations that could not be accounted for during a SMAC experiment. These considerations informed the next iterations of design.

3.4 Summary

One of the aims of this research is to classify previously unclassified and unrecognised techniques for mechanism synthesis, as many mechanism designers share the same confusing experience at the "fuzzy" front end of linkage synthesis. Necessity often drives innovation and, in this case, it has produced useful tools worth sharing.

A partial set of results from this process have been compiled in Appendix D. The insight gained from observing different configurations and dimensional combinations perform through a range of motion was used to refine the design specifications and inspire new solutions during the design of the Skiboard.

The primary benefit of this tool is that the designer can interact with the model visually and receive meaningful, easily-understood feedback from the program about behaviour of a particular design. This feedback and automated experimentation with different dimensional combinations can help the designer select a suitable mechanism from a group of candidates and keep an atlas of concepts trialled. Patterns of behaviour and sensitivity information can lead the designer towards an optimal combination of link dimensions.

Another benefit of SMAC is that it does not require the designer to understand the kinematics of the linkage being tested. It removes the user from tedious calculation and analytical analysis without removing him or her from the process entirely.

Operating in a 3D modelling environment provides an additional advantage when it comes to detecting singularity and analysis the kinetics of a design. A 3D model in SolidWorks can be easily constrained for a COSMOSMotion simulation. This advantage is not provided by any existing 2D synthesis programs.

One of the main drawbacks to using SMAC for linkage synthesis is that the user interface requires that the designer has basic knowledge of Visual Basic for Applications. As described in Section 3.2.1.3, the system variables (or dimensions) must be identified manually since, at the code level, SolidWorks assigns unique names to every part, feature and dimension of every model created. Each model created possesses unique path IDs for each dimension, thus allowing the user to identify these dimensions in the program setup without interacting with the VBA code would be very difficult to accomplish.

Another drawback to SMAC lies in the fact that it is a less thorough dimensional optimisation technique than many other existing techniques and is better suited as a synthesis tool. The user must choose the range of variables to be tested and how much of the design space is sacrificed to save resources. The overlooked sections of the design space could contain a solution, which means that this program cannot ensure that potentially suitable dimensional combinations are not missed.

Missing suitable dimensional combinations could result in an erroneous dismissal of a particular type of linkage as a solution. However, for some mechanism design tasks, and certainly in the case of the Skiboard, the possibility of missing solutions was worth having access to interactive, easy-to-use, automatically iterative software. Through exploring the benefits and drawbacks of the SMAC program, another program concept was developed. This new concept, called PSEO is introduced in Chapter 4.

Chapter 4.

Parametric Sketching and Evolutionary Optimisation (PSEO)

To improve upon the existing SMAC program, a concept for a sketch-based experimental synthesis and optimisation program was developed. The primary user interface for this program is based in a 2D Blocks sketching and constraint modelling environment. It will be referred to as Parametric Sketching and Evolutionary Optimisation or PSEO.

PSEO is a linkage concept experimentation program that is capable of more thoroughly analysing the design space than SMAC. It explores the design space in an automated, informed and iterative fashion that is removed from the influence of the designer. This increased level of automation will greatly decrease the chance that a potentially suitable solution will be missed and increase the chance of finding a truly optimal set of linkage dimensions. Thus, PSEO is better suited as an optimisation tool, rather than a synthesis tool such as SMAC.

Additionally, the PSEO concept aims to embed an automated solution comparison tool that can assess how “close” a particular solution curve shape is to the desired solution curve without requiring a check by the user. This comparison tool will allow the program to iterate towards more ideal solutions and away from unsuitable ones in a way that is better suited to mechanism design than classical optimisation techniques. This extra level of automation will significantly decrease the time required by the designer to search a particular concept space for possible solutions.

To accomplish the task of increasing the automation of the design process, the user interface was moved from the solid modelling environment in SolidWorks to the Blocks parametric sketching interface. While visualising a mechanism as a two-dimensional sketch might be more difficult than working with a three-dimensional model, it allows for the testing and easy manipulation of many more dimensional combinations than with a complete solid model. There are other advantages to this interface, including an enhanced opportunity for the designer to incorporate graphical synthesis methods into the design environment. Burmester sketching curves and other sketching helps can be also overlayed onto the 2D model.

PSEO is a unique automation tool that, with more time and software programming expertise, could be developed into a useful design help for designers faced with complex synthesis problems. The sections to follow describe the software tools comprising the PSEO concept and provide example screenshots to show what the user would experience while using the program.

4.1 PSEO Program Structure

The PSEO program integrates four stages of operation. Each of these stages, for the present discussion, has been assigned a separate software package. In future stages of development, a more cohesive flow between the software components might be established. However, the program’s basic structure and functionality will remain the same.

Figure 28 shows the flow of the PSEO program. The green box highlights the processes that are iterative. The experimental optimisation cycle can be followed using the chart by starting at the upper left-hand corner with the creation of a linkage in the Blocks sketching program within SolidWorks. A cycle completes when the one optimal solution has been found or when the program reaches a maximum number of iterations, depending on which of these situations occurs first.

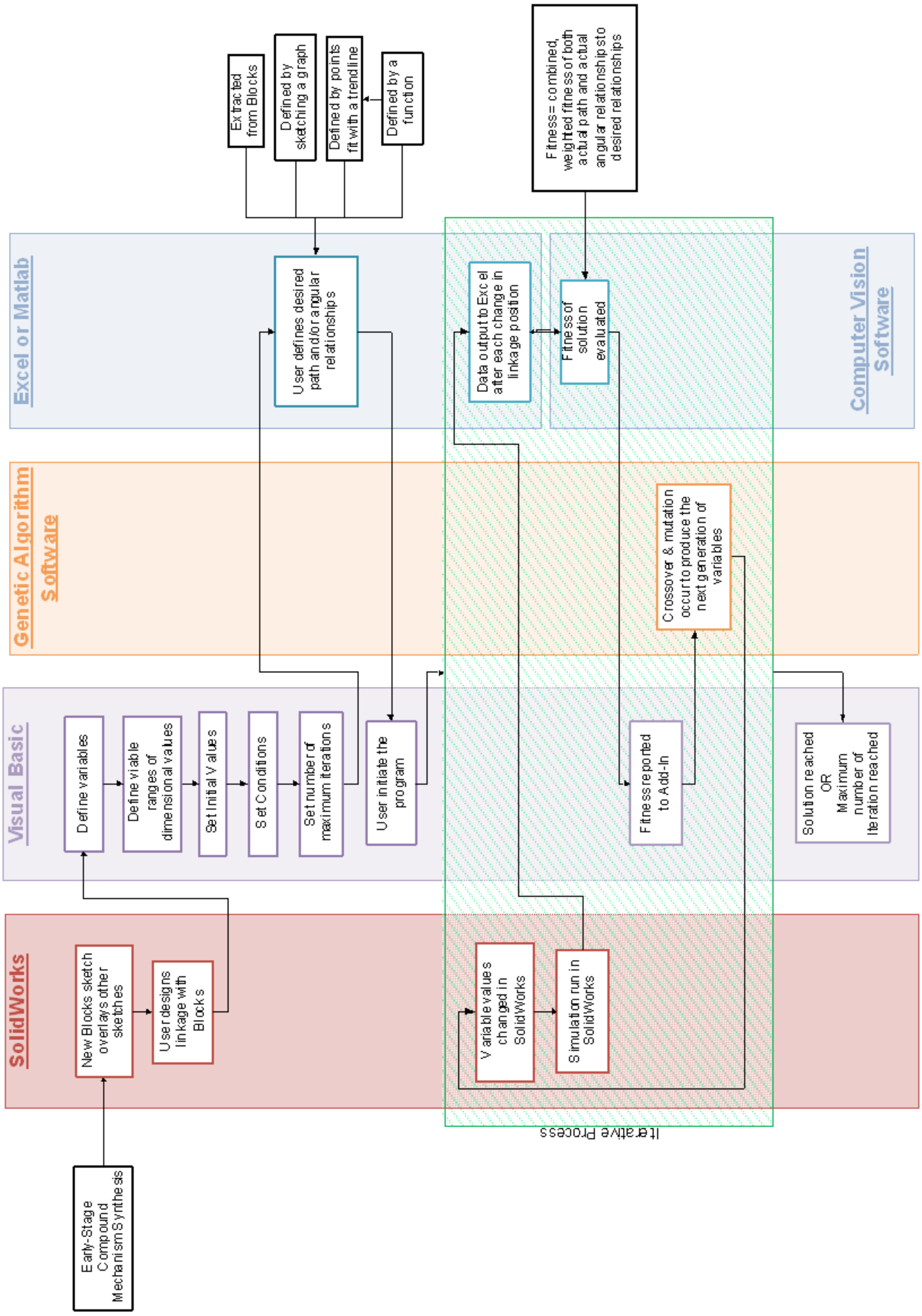


Figure 28: Flowchart of PSEO Program

Sections 4.2 to 4.4 detail the function of each of the four stages of operation, following the flow chart from left to right.

4.2 Parametric Sketching in SolidWorks

Blocks, a sketching package contained within SolidWorks, is a type of geometric constraint program (GCP). GCPs facilitate the easy and intuitive formulation of complex kinematic synthesis problems within the sketching mode of a parametric design software package (Kinzel, Schmiedeler et al. 2006). In SolidWorks, links can be sketched as Blocks and constraints can be added between the Blocks or points on the Blocks to create a kinematic model of a linkage.

The designer can also sketch Burmester curves over the parametric model by overlaying a new sketch. This incorporation of graphical synthesis methods can be helpful in the early-stage concept development of simple, under-constrained linkages. Graphical synthesis methods are often useful in early stages due to the visual feedback that is provided to the designer by sketching and the ability to solve problems without needing to understand the underlying complex mathematics. (Reifschneider 2005)

4.2.1 Creating a Parametric Linkage Sketch

The PSEO method relies on the sketching and Block creation environment in SolidWorks. Each complete linkage starts as one sketch. Each of the links is represented in 2D by line(s) and/or curve(s). Each discrete link is then made into a Block, which is a 2D representation of a solid part. A set of sketch entities that are part of the same Block remain fixed relative to each other so that the Block moves through the sketch space as a solid object.

The next step in creating a parametric model is to set the motion constraints between the links, known as Relationships in SolidWorks. A pin joint, for example, can be simulated by assigning a “coincident” mate to the endpoints of two Blocks or links. A guide to imposing geometric constraints with a GCP such as Blocks in SolidWorks is contained in (Kinzel, Schmiedeler et al. 2006).

An example 2D linkage mechanism is shown in Figure 29. This parametric sketch is a 2D representation of a Skiboard concept. Note the Blocks listed in the feature tree at the left, which represent the links of the mechanism.

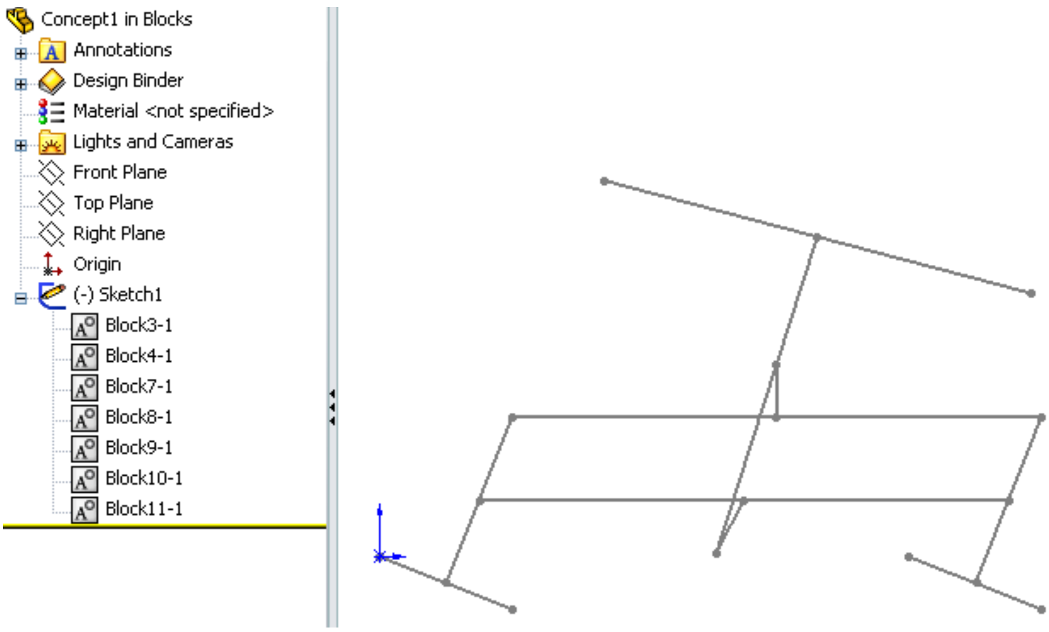


Figure 29: Skiboard in Blocks

Once the 2D model is properly constrained, the user must assist the program in identifying the model, the links and which dimensions on those links are variable. First, the location and sketch name of the file must be identified by the user, as shown in Figure 30. The completion of this dialog box will prompt the user to further define the linkage.

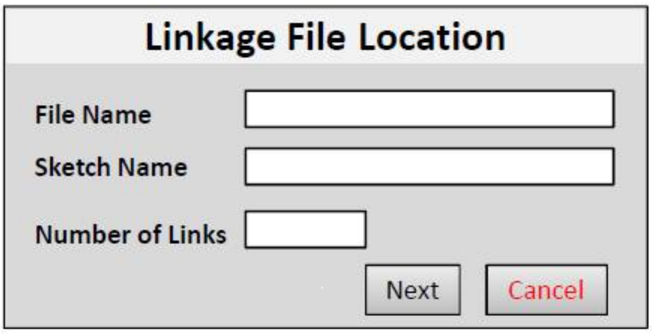


Figure 30: Linkage File Location Dialog Box

4.2.2 User Definition of Test Conditions and Termination Criteria

Visual Basic for Applications, or a similar program, interacts with the user to establish the experimental conditions and termination criteria. Once this initial setup process is complete, the automated portion of the program takes over to carry out the experiment and analyse the results. One important user-based step is to identify which links contain variable dimensions. This can be done easily via a user form such as the one in Figure 31.

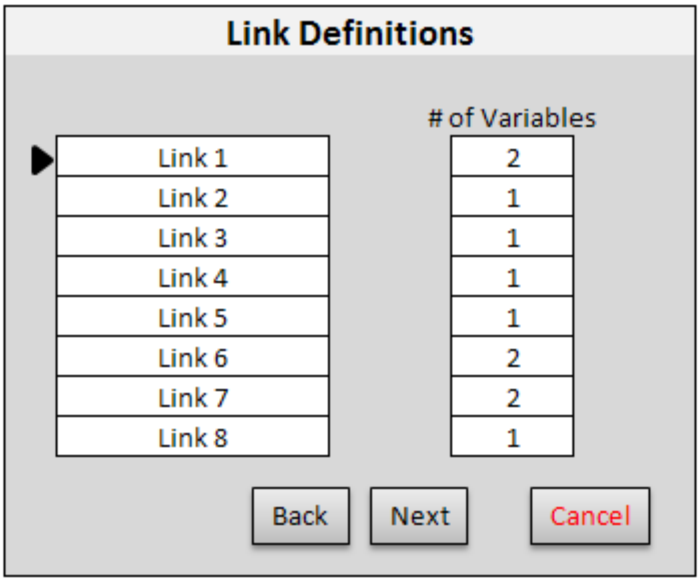


Figure 31: Linkage Definition Dialog Box

As shown in Figure 32, a range of test values is defined by the designer for each variable dimension. The sample dialog box in the figure shows two variable dimensions for Link 1 of 8. The text box labelled "dimension name" is filled in with the name given by the GCP program to the dimensions being changed. In the case of Blocks in SolidWorks, dimensions names come in the form D1, D2 and so on.

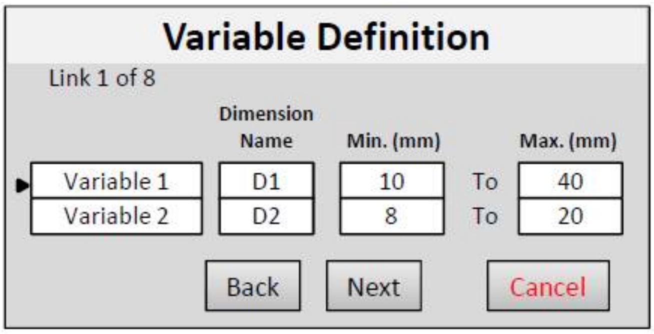


Figure 32: Variable Definition Dialog Box

From the ranges of variable values defined by the user, PSEO will, in an automated fashion, randomly modify and recombine linkage configurations to produce new test configurations. The embedded genetic algorithm package will guide the set of candidate linkages towards a “best fit” solution. The genetic algorithm component of PSEO is described in more detail in Section 4.4.

Since the algorithm alters dimensional combinations at random, it is likely that some infeasible configurations will be encountered over the course of the optimisation process. As discussed in Chapter 3, infeasible combinations can produce loop closure errors (where two links that are supposed to intersect, but do not) and upside-down rebuilds of the linkage mechanism. Unlike SMAC, PSEO can handle rebuild errors efficiently, as one erroneous rebuild will not cause a series of others within the GCP environment.

If one infeasible construction is tested, the associate errors will not crash the program. Instead, the unstable model is given a null fitness value and culled from the set of candidate configurations, to be replaced by a viable one. Upside-down rebuilds will not occur because, in a 2D model, the constraints and arrangements of links cannot be reversed from front to back or top to bottom as is possible in a 3D modelling environment. This robustness could not be ensured by SMAC, which presented major obstacles to exploring the entire dimensional design space and fuelled the search for a new type of software environment.

4.2.3 Concept Experimentation in PSEO

Motion experiments are carried out in PSEO in much the same way as in SMAC. A dimension is assigned to a driving link (or links) and motion is simulated by iteratively changing this dimension. The driving dimension can be an incremental angle of rotation or sliding distance, defined by an angular or linear dimension, respectively. Since forces cannot be accounted for in models comprised of parametric sketches, the link designated to be the input link can be chosen arbitrarily without effecting the results of the kinematic test. The relative motion of the links will be the same regardless of which link is driving the motion.

Experimental iterations, meaning iterations from the testing of one configuration to the next, are handled by the genetic algorithm portion of the program, which is explained in Section 4.4. First, the fitness or correlation determination algorithm is discussed.

4.3 Experimentation Results and Correlation Determination

The correlation (or fitness) determination technique for this software relies on computer vision because it allows for scale-invariant shape comparison. Point-by-point correlation comparison, in contrast, has the potential to poorly rank solution linkages that create nearly suitable motion due to a simple mismatch of scale. The use of computer vision also avoids the selection of "suitable" solutions that contain unwanted concavity fluctuations, which is a likely occurrence when using classical optimisation methods. Figure 33 demonstrates this phenomenon.

The black trend line, which has a relatively high R^2 or correlation value with the green line, contains three concavity fluctuations. For data fit problems that are unrelated to mechanism design and physical movement, such a high-order fit curve would usually be an acceptable solution. However, since the solution curve represents actual physical motion, its smoothness is a critical consideration. Concavity fluctuations would be felt as bumps in the case of a device like the Skiboard, which would produce undesirable motion and control characteristics for the user.

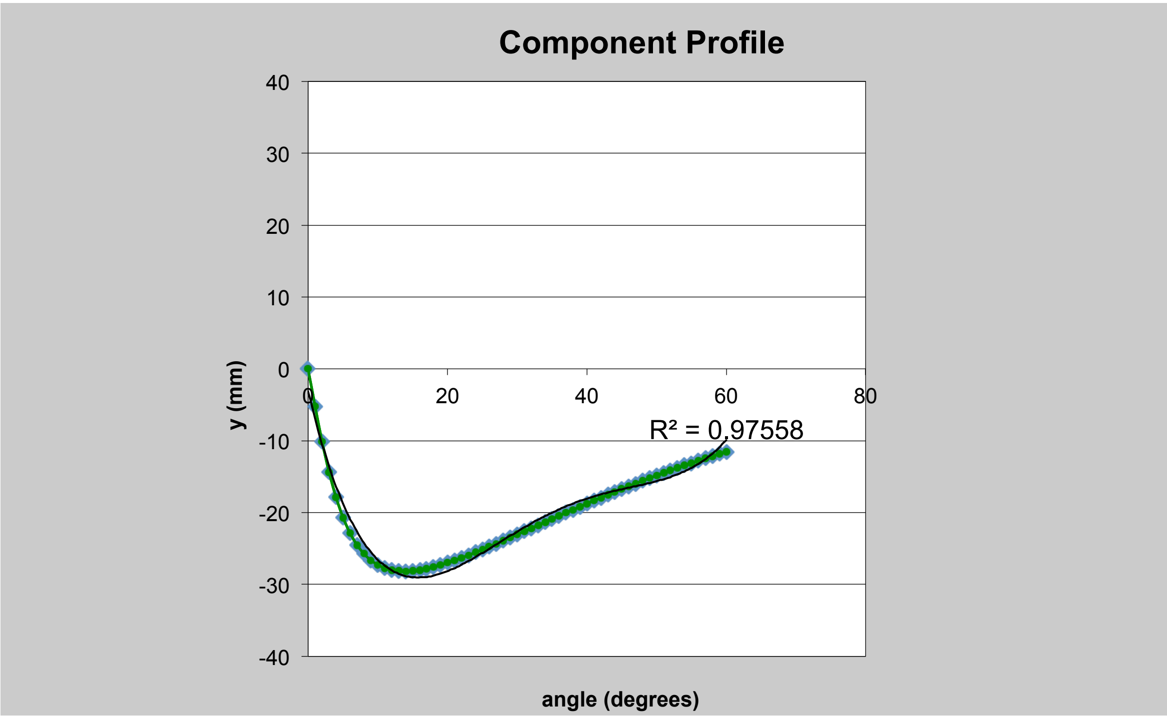


Figure 33: Curve Fit

For its simplicity and scale-invariant shape correlation abilities, the planar object recognition algorithm developed by Hann et al. (2003) is an ideal candidate for assigning fitness to solutions in PSEO. The algorithm relates two curves by choosing common reference points and applying projective transformation. Then, equally spaced points are placed along the transformed curves and the error between corresponding points is calculated. A detailed explanation of this algorithm is available in (Hann 2001).

An algorithm such as Hann's can be used to evaluate solution curves associated with path, motion or function generation with little run time expense. Additionally, fitness can be determined in a way that favours solution mechanisms that match the overall smoothness characteristics of the objective motion curve. It avoids the selection of solution curves that match up at certain points but deviate from the desired shape elsewhere along the path of motion.

4.4 Genetic-Algorithm-Driven Iteration

Perhaps the most significant advancement over the SMAC process lies in the ability of the PSEO software to automatically recombine linkage configurations, test the combinations and use the feedback to automatically influence the next "generation" of candidate linkages. This capability is made possible by an embedded genetic algorithm package that helps guide the exploration of the solution space towards an optimal result. In this way, PSEO is more of an optimisation tool than purely an experimentation tool.

The genetic algorithm will function according to the structure shown in Figure 34. This structure is typical of evolutionary algorithms, adapted from (Renner and Ekart 2003). Within the algorithm structure, note the reference to the correlation algorithm presented in Section 4.3.

Once the user-controlled setup of a virtual mechanism experiment is complete, the algorithm will guide the testing procedure. It starts from an initial set of candidate configurations consisting of a number of randomly modified copies of the user-specified linkage mechanism. An experiment is conducted for each configuration.

The genetic algorithm refers to the correlation algorithm to check the fitness of each configuration's motion to the desired motion. Unless, by chance, the initial set of linkage configurations contains a suitable solution match, the algorithm creates a new configuration set or "population" with which to begin the next iteration.

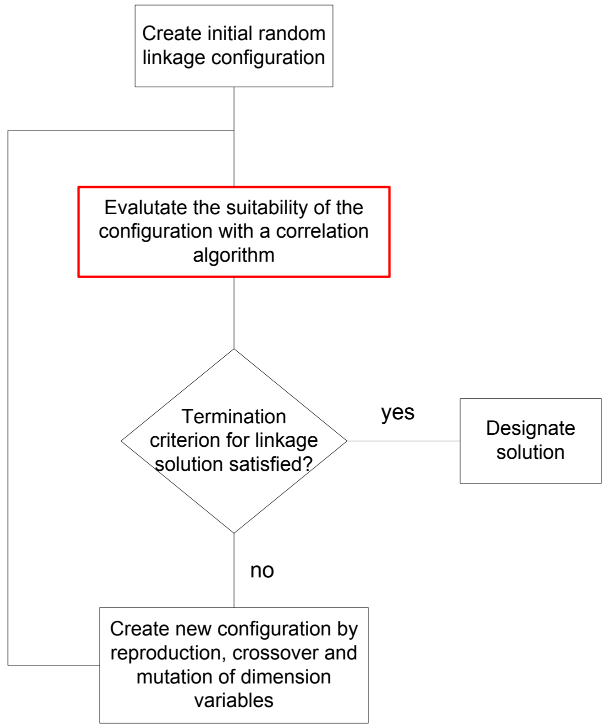


Figure 34: Genetic Algorithm Flowchart

The second configuration set and every configuration set thereafter is created by discarding some of the least fit configurations and replacing them with new configurations constructed from the "survivors". Each new configuration is created by taking some variables from one surviving configuration and the rest from another (*crossover*). The population is further manipulated by modifying or perturbing randomly chosen variables within the configurations (*mutation*). Configurations that are shown to be strongly unsuitable by the correlation algorithm are not favoured for use in crossover and, essentially, die off. Configurations that perform more favourably, however, are kept to have their variables reused or *reproduced*. (Capello and Mancuso 2003)

The algorithm maintains a collection of solutions. Therefore, if the designer wished to enable a reporting function at the end of an experimental run, the algorithm is capable of creating an atlas of the most favourable solutions. In this way, designer interaction is preserved and the experimentation process can inform the designer rather than arrive at one solution completely independently.

4.5 Summary

In the field of mechanism design, the task of synthesis is "still largely a challenge" (Lipson 2004). PSEO addresses some of the challenges involved in synthesising linkages by providing the designer with an automated concept experimentation and solution analysis platform. The program eliminates the need for the designer to create tables of variables to test and relieves the burden of visually checking every tested solution for fitness.

Since PSEO relies on 2D rather than 3D linkage models, it can continue to run after encountering a loop closure error without passing rebuild errors on to the next configuration. It also allows the designer to incorporate graphical sketching methods and use reference sketches to create and influence their solution concepts. The embedded genetic algorithm moves the experiment towards better solutions in an efficient manner.

As is typically the trade-off with increased automation, the user interface of PSEO is more complex and requires more setup than SMAC. In addition, the parametric model created in PSEO cannot be immediately used for kinetic analysis. Forces and tests for singularity must be considered as a separate step in the iterative mechanism design process by either creating a 3D solid model for use with a motion and force analysis package or by building a physical prototype.

However, PSEO offers mechanism designers a level of hands-on design that currently available genetic algorithm-based tools for topology synthesis are unable to provide. It is novel in its interactive experimentation approach to applying evolutionary algorithms to the problem of linkage synthesis and optimisation. Furthermore, it is capable of tracking and cataloguing the progress of the design process and offering insight into the sensitivities of the output motion to the topology and dimensions of solution concepts, thereby developing the intuition of the designer.

Chapter 5.

Pre-Production Concept Design

This chapter returns to the topic of the Skiboard design and explores the design process behind the complex linkage mechanism. The refinement of the design specifications and the progressive intuitive understanding of the mechanism's behaviour took place through experimentation. An explanation of the process and results of the iterative and informative design process is contained in the sections to follow.

5.1 Progression of Design Specification

The initial brainstorming sessions for finding solutions to the Skiboard design problem involved considering the motion and function generation simultaneously. None of these initial sessions yielded mechanisms that satisfied the design requirements better than previous concepts. It was later discovered that there were two fundamental obstacles blocking the progress.

First, since this design task involves the fulfilment of two functional requirements at once, motion- and function-generation, approaching it as one "black-box" mechanism synthesis problem proved ineffective. Bearing in mind that the solution space actually consists of two intersecting functional requirement problems, separating the task into two separate functional requirement problems produces more effective solutions and was an important part of the design process. The interrelated nature of these problems requires that this process is iterative in nature, as the impact of one functional requirement solution on the other is important.

The second and more significant obstacle was a poorly defined list of design specifications. Since this design problem involves creating a "feeling-based" object for direct consumer use, it was difficult to define the requirements in technical and precise enough terms to represent them graphically or mathematically. A significant amount of time was spent clarifying these specifications and expressing them quantitatively. As product designer, Pugh, observed:

> *"The absence of a PDS will result in designs that almost without doubt will fail in the market: poor PDSs lead to poor designs; good PDSs do not necessarily result in the best designs but they do however make that goal at least attainable" (Pugh 1991).*

Table 4 presents a comparison of the initial sets of specifications and the modified PDS that resulted from initial research and experimentation. Note the qualitative nature of the specifications on the left as compared to the quantitative nature of those on the right.

Table 4: PDS comparison chart

	Qualitative Specifications to Quantitative Specifications	
Function		**Function**
Skis tilt together		Skis always parallel and laterally stationary relative to each other
Minimal gearing (if any) between board and skis		Board to skis gearing ratio between 1:1 and 3:4
60-degree absolute minimum angle of ski tilt		60-degree maximum ski tilt
Mechanism keeps rider's force over skis		Horizontal position of board centre within bounds of space between skis
Motion		**Motion**
Rider is stable near board centreline		Stability 40 mm laterally about the centerline
Controllable range of movement after initiation point		Elliptical rolling surface
Gradual initiation of movement		Rolling surface radius approximately 100 mm
Impact will not result in a change in ski tilt		Motion behaviour force-independent (as defined by rolling path trochoids)
Other Constraints		**Other Constraints**
Planar linkage		Planar linkage
Minimal size		Maximum vertical distance between board & skis 165 mm
Few moving parts		Few moving parts
		Horizontal position of board centre within bounds of space between skis

*Specifications in italics fall outside of the scope of this project.

The specifications under the Function heading define the function generation requirements of the design problem. Those under the Motion heading define the motion generation requirements. The function-related specifications are examined first in more detail.

5.1.1 Function Generation

The final function generation specifications are listed below:

- Skis always parallel and longitudinally stationary relative to each other
- Board to skis gearing ratio between 1:1 and 3:4
- 60-degree maximum ski tilt

The parallel ski requirement was established so that the Skiboard would be able to turn smoothly without chattering. (Witherell 1988) The sidecut of a ski is the feature that determines the turning radius. Hence, it is naturally a requirement that the sidecut curves of the two skis are concentric.

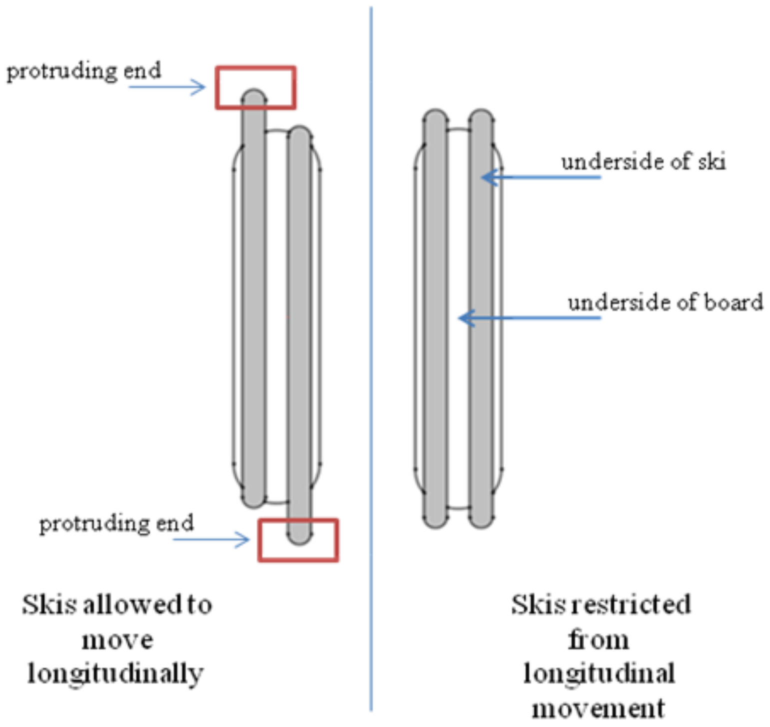


Figure 35: Longitudinally Moving vs. Longitudinally Stationary Skis

The skis are to be kept longitudinally stationary with respect to each other because the Skiboard will likely be used mostly to perform tricks in snow parks. In a snow park situation, it would not benefit the rider to allow the skis to move fore or aft of the deck surface, as protruding components are likely to catch on ramps or rails. Figure 35 illustrates the difference between longitudinally moving and longitudinally stationary skis.

The gearing ratio and maximum ski tilt requirements for the mechanism were restated in qualitative terms based on a Human Interaction Model created in Excel. This model will be explained in more detail in Chapter 6.

5.1.2 Motion Generation

Below are three of the original specifications for motion generation, which are addressed first:

- Controllable range of progressive movement after initiation point
- Gradual initiation of movement
- Impact loading will not result in a change in angulation

This original list of board motion requirements was perhaps the most problematic section of the original PDS. The challenge of creating a mechanism that would offer a gradual initiation of movement and a controllable range of motion thereafter immediately gave way to the idea of using a spring or elastic material to provide resistance. Figure 36 shows a first attempt at adding resistance with springs in Concept 0.

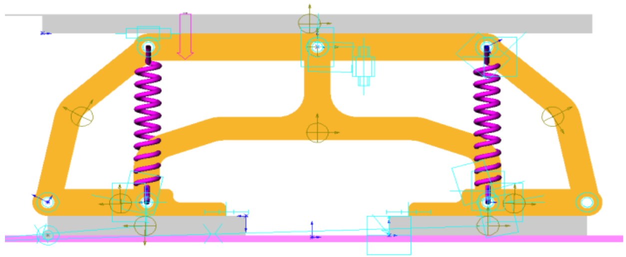


Figure 36: Concept 0 with Springs

Concept 0 was tested in the COSMOS Motion environment in SolidWorks. Virtual springs with three different stiffness values were tested to assess whether or not the concept would produce gradual tilt for the rider.

Figure 37, the output data from COSMOS Motion, shows that the addition of springs does make the tilting of the board occur in a more gradual fashion as the force of the rider moves away from the centre of the board. However, this progressive board tilt is produced at the expense of the range of motion of the skis. It is also important to note that the COSMOS Motion tests performed on Concept 0 only measured the response of the device to static loading. The resistive effect observed in the test results would not be consistent and predictable under normal, dynamic riding conditions.

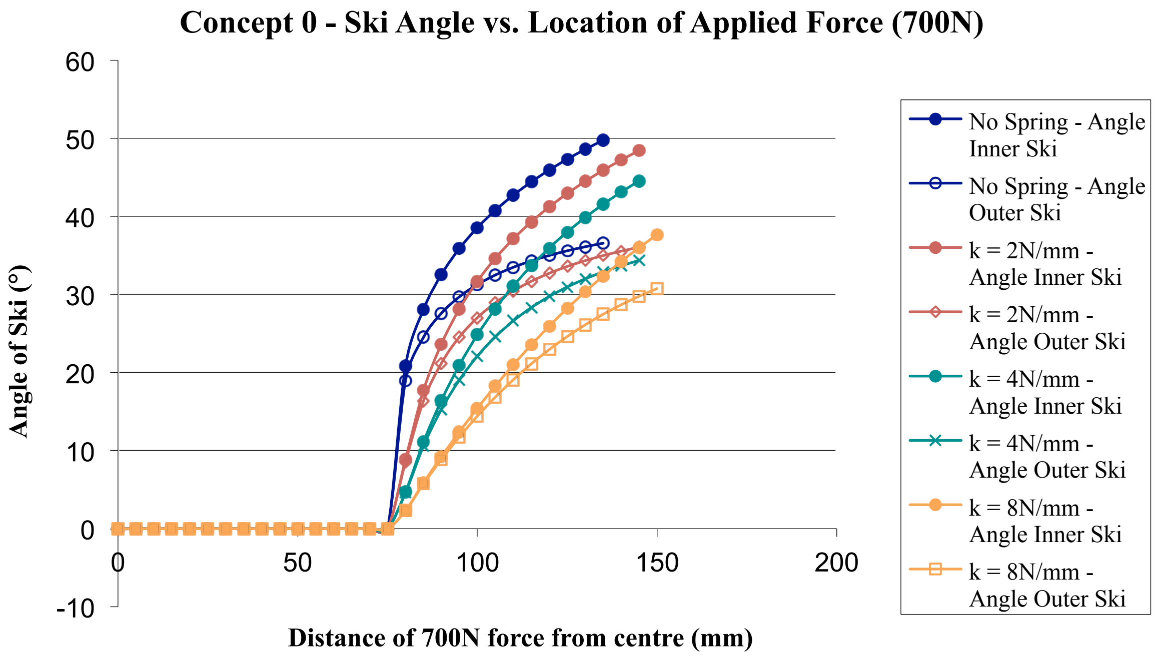


Figure 37: Concept 0 Test Results (For a spring stiffness of 8N/mm, for example, the maximum ski tilt is under 40°[2])

In particular, impact loads are likely to be applied to the Skiboard during typical downhill runs as the rider traverses bumps and dips in the snow surface. This type of loading is particularly prone to occurring in skate park riding conditions due to the sudden impact of the board on ramps, rails and other abrupt surface changes. Impact and suddenly applied loads can abruptly magnify the force on a load-bearing member. (Collins, Staab et al. 2003)

Suddenly applied loading is detailed here as a special type of impact loading that occurs when the "striking mass" – the rider, in this case - is just in contact with the load bearing surface and suddenly applies their entire body weight from zero height. An undulation in the terrain could easily produce this situation. For suddenly applied loads, the actual downward force experienced by the board would be twice the person's body weight. If the rider were to jump onto the board from a height, the impact load would be of a greater magnitude, depending on the height from which their feet fall to reach the board. (Collins, Staab et al. 2003)

Thus, the inclusion of a spring or other resistive device renders the design concept unsuitable for meeting the requirement concerning impact loading. In particular, the displacement characteristics of springs and elastomer bands are force-dependent and the applied force becomes a factor controlling the tilt of the skis in addition to the rider's resolved force position relative to the centre of the board. Hence, in the presence of springs, the board tilt angle becomes a function of rider behaviour, mass and terrain conditions.

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[2] The Concept 0 mechanism did not tilt the skis in parallel. Therefore, according to the current PDS, it was an unsuitable solution both because it did not provide parallel ski tilt and because the design was not resistant to impact loading.

Although the force-dependent nature of the springs can be observed in Figure 37, a clearer comparison is provided in Figure 38. This figure shows the effect of doubling the force applied to the Concept 0 mechanism with springs set to a stiffness of 8 N/mm. The maximum tilt of the inner ski is nearly 10° more if a 1400 N force is applied rather than a 700 N force. Hence, the Skiboard would be more difficult or less difficult to turn depending on the rider's body mass, which is an undesirable condition to place upon possible users because the internal mechanism of the Skiboard is intended for use by any type of rider.

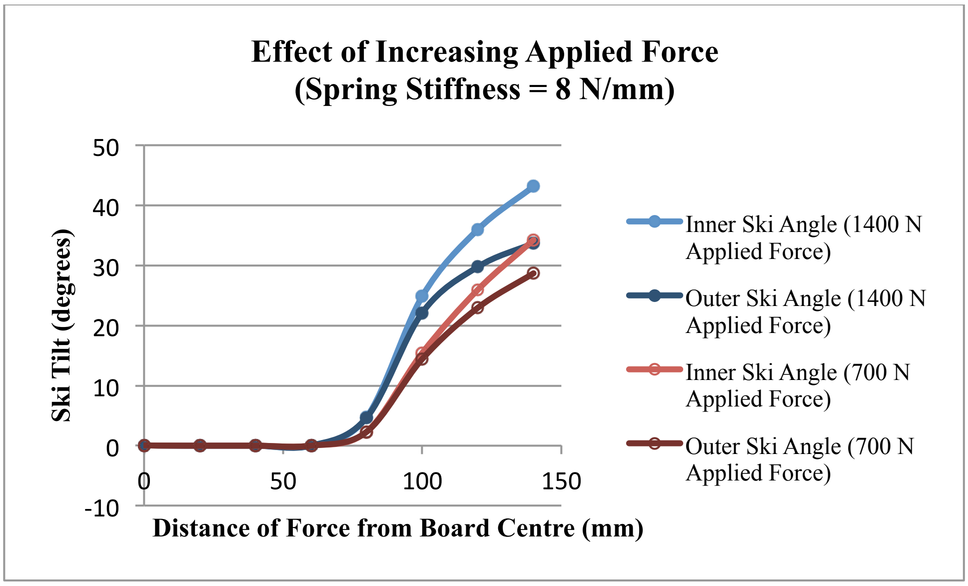


Figure 38: Effect of Increasing Applied Force with Spring-Loaded Mechanisms

In the case of suddenly applied loading or impact loading, a spring would also produce a restoring spring-back effect. As the suddenly applied load eased, the spring would, in reality, need to support only half of the force that it suddenly experienced at the onset of loading at twice the displacement. The resulting restoring force would overcome gravity and the spring would oscillate, until the system reached equilibrium. This behaviour is shown in Figure 39.

On ski fields and in skate parks, changing terrain such as uneven and undulating snow-laden surfaces dictates that the rider will apply some magnitude of variable impact loading to the board throughout use. As a result, resistive devices were discounted as possible design solutions. Hence, an entirely linkage-based approach was required to provide this gradual motion effect.

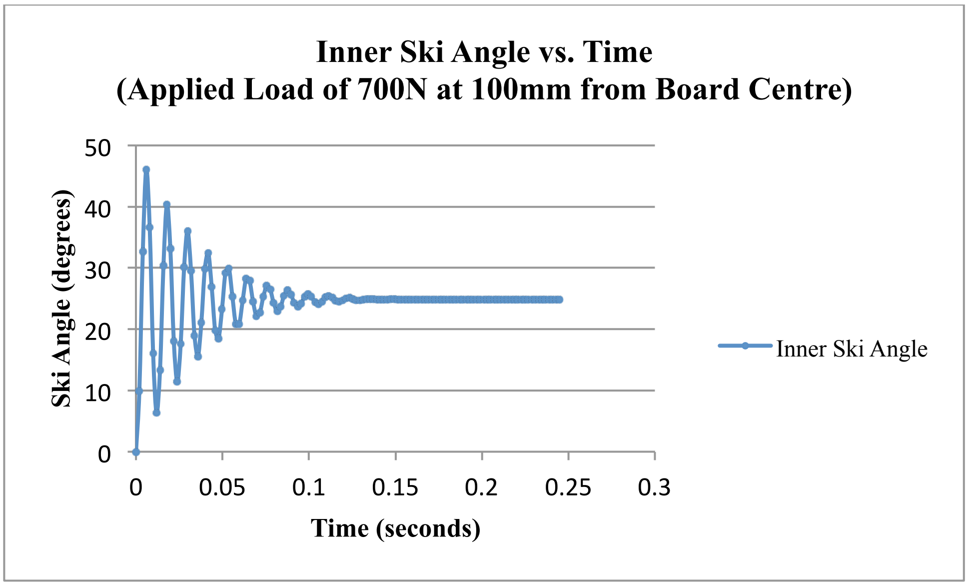


Figure 39: Oscillation of Ski Angle due to Spring for the Case of Concept 0 in Figure 36

After removing springs from the range of solutions, the problem of creating gradual and easily controllable board movement remained without many viable solutions. It became clear that the board's desired motion needed to be modelled to more effectively describe the design specifications. In other words, the qualitative "gradual movement" requirement needed to be replaced with a graphical or numerical, quantitative representation. The approach led to exploring the concept of hesitation and defining a new set of motion generation specifications.

5.1.3 Hesitation

The concept of hesitation was explored as a way to achieve a resistive force effect with a linkage mechanism rather than an ordinary resistive device such as a spring or elastomer.

For the board to provide a feeling of progressive tilt for the rider, it must essentially come to rest at incremental angles of tilt depending upon the placement of the rider's resultant force. The board's tilting angle must remain quasi-static in each of these rest positions until the rider shifts his or her force, and, in effect, the system, to the next temporary resting angle. This series of gradually steeper inclined rest positions produces an input-output relationship similar to that achieved by adding a resistive force member. As the resolved force of the rider shifts away from the board centre, the incremental rest positions provide that person with a measured, controllable progression of increasing angulation. A sketch representing this idea is shown in Figure 40.

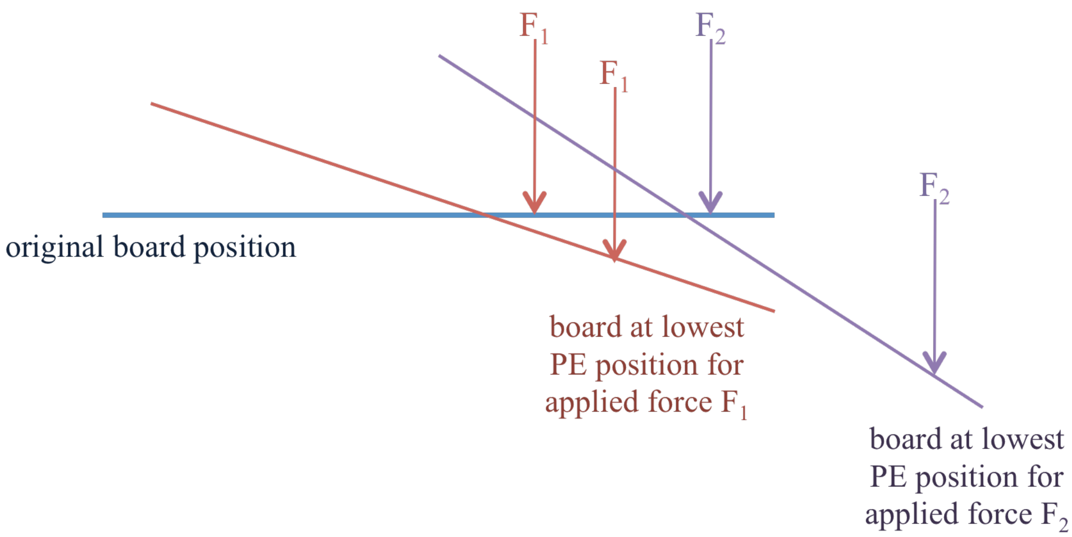


Figure 40: Illustration of Shifting Centre of Rotation

Note the way in which the position of the resolved force on the board is always the centre of rotation for the board. Of course, from an energy perspective, the shifting centre of rotation cannot move horizontally as shown above. The energy put into the system by the rider must be balanced by moving the board downward. The two concepts presented here, of a shifting instantaneous centre of rotation and the importance of considering the balance of forces (energy), are discussed in detail later on in this chapter.

As previously mentioned, the behaviour described in this section can be classified as motion generation, rather than path generation. The Skiboard's desired path of motion cannot be achieved by assigning a path to one particular point on the object or even to several points. In particular, given it intended use, it is important to consider the position of the object in three degrees of freedom (angle of rotation (θ), horizontal position (x) and vertical position (y)).

When thinking in terms of mechanism design, the term dwell is appropriate in describing the "coming to rest" of a point along a path. This particular term and the behaviour it illustrates are associated with cams and intermittent motion devices, such as a Whitworth quick return (Uicker, Pennock et al. 2003). These two types of mechanisms are unique in their ability to bring a point to a full stop with respect to the mechanism's frame of reference. No other type of mechanism is able to achieve this effect (Harding 1965). Unfortunately, it is impractical to attempt to apply either of these types to the current design because infinitely many point paths must be brought to a rest through the body's range of motion as opposed to just one coupler point in the case of a cam or quick-return linkage.

However, there is another approach to the problem of bringing a point to rest along a path that is more applicable to the current design task. This alternate approach involves considering the concept of approximate dwell, a behaviour that can be replicated by almost any type of mechanism. This behaviour was first researched by Harding (1965) who gave it the name hesitation. Hesitation occurs when a point either "pauses" along its path of motion before continuing along its original trajectory or reverses its direction completely.

The point comes to a stop and velocity equals zero for a brief instant before the point continues. A sustained full stop in one or all of its directions of motion does not occur during hesitation. For many design problems requiring a dwell-type solution, hesitation behaviour is sufficient for satisfying the functional requirements (Harding 1965). Figure 41 shows an example of a linkage that produces this behaviour.

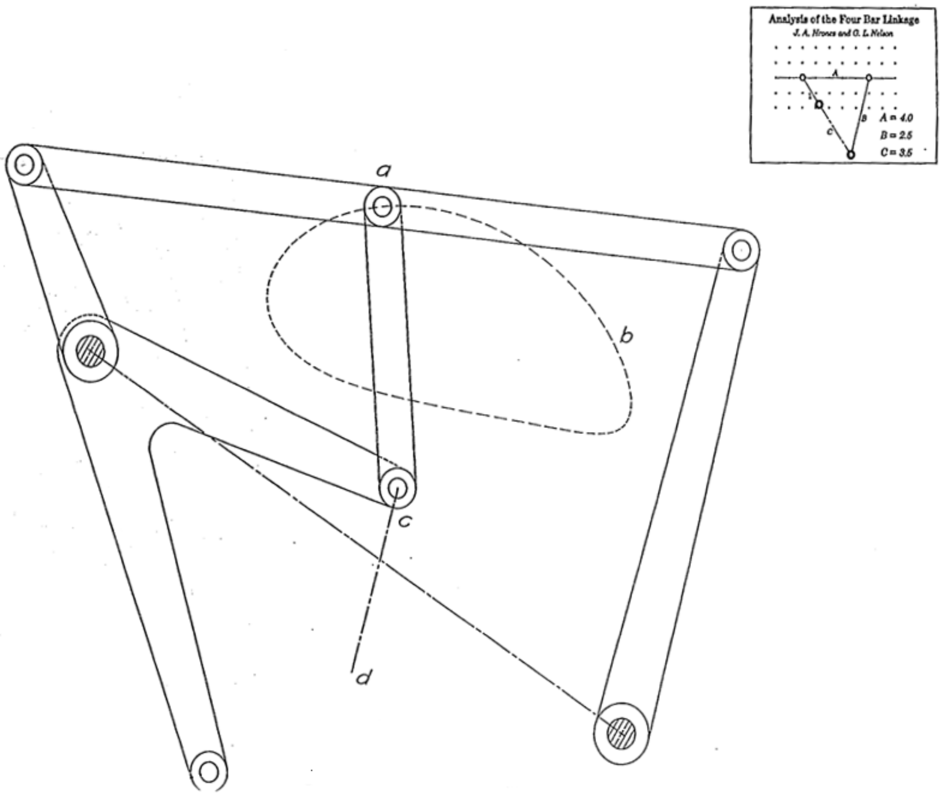


Figure 41: Dwell period from circular arc path (Hrones, 1951)

According to Norton (1992), the usual approach to designing dwell linkages is to use graphical synthesis methods. This author suggests the synthesis of a four-bar linkage and the addition of a dyad to provide the dwell behaviour. This construction technique was used to inform the design of the Skiboard.

As it applies to the Skiboard, the motion requirement of the board is simplified by stipulating that the points along the board exhibit dwell behaviour and reverse their trajectory from a direction of travel of downward to upward. This dwell criterion is in contrast to requiring that they reach a full stop. According to Harding (1965), this type of hesitation could be classed as a negative degree hesitation.

By considering this concept, it was soon realised that guiding points to reverse direction in opposition to the direction of the applied force would produce a series of real, stable (albeit temporary) rest positions. The resulting infinitesimal point paths along the board would resemble a v- or hook-shaped path. Each point would have the potential to come to rest at the vertex or "trough" of its path – in the lowest potential energy position or the point along the path that is closest to the ground.

Figure 42 illustrates the behaviour of a board following this gradual transition from rest position to rest position. The approximate paths of two points along the board have been traced. The board is shown at its lowest potential energy position.

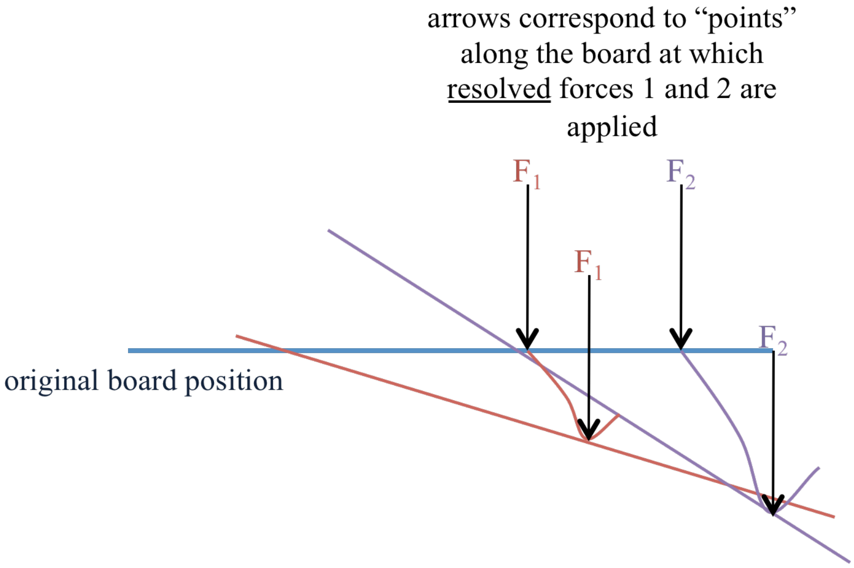


Figure 42: Board at "Rest" in Point Path Minima

The resolved applied, vertical forces, F_1 and F_2, in Figure 42 are represented by arrows pointing in a negative, y-axis direction. In use, centripetal forces would change the direction of the resolved force towards the centre of the board. However, for demonstration purposes, it is assumed that forces 1 and 2 are being applied to the board under static conditions.

From a force analysis perspective, it makes sense that the board would cease its vertical descent when the applied force location reaches the "trough" of its path. In particular, the rider would be physically incapable of lifting their own body weight by applying their own body weight in the form of a force toward the ground. Hence, upon reaching the bottom of a trough, the point on the board following the trajectory would effectively remain at that low energy point until the rider's weight is shifted to the opposite side of the board. When the weight shifts, the point in question is lifted back along the path of its original descent.

Once the need for this set of hook-shaped paths was identified, the next challenge was to represent the overall motion of the board graphically. The goal was to obtain a function or series of discrete positions that would inspire design solutions. Ultimately, the simple concept of a straight object being rolled along the perimeter or "surface" of a circle led to a clearer understanding of the Skiboard motion and a more practical design specification.

5.1.4 Circular Rolling Surface Model

If a straight object rolls - without sliding - over a circular surface, the points along the straight line follow paths similar to those described as desirable in the preceding section. Figure 43 illustrates this behaviour:

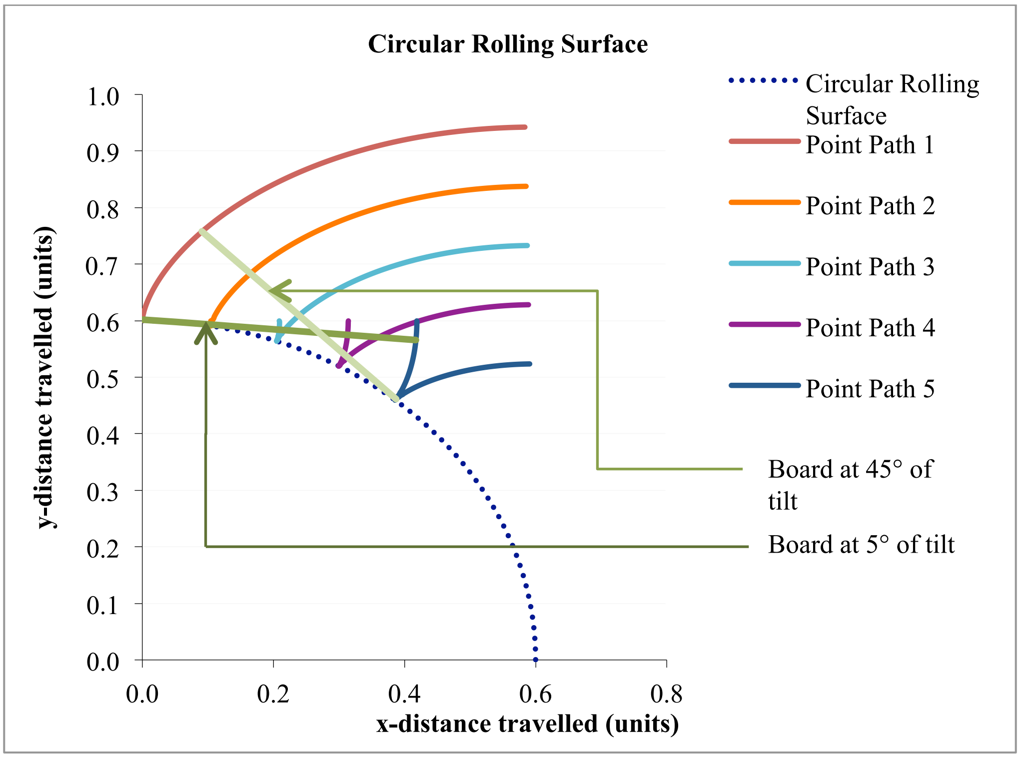


Figure 43: Circular Rolling Surface

The resulting v-shaped point path curves will henceforth be referred to as trochoids. The portions of the trochoids that are traced before reaching their minima can be either shortened or lengthened by changing the aspect ratio between the circle radius and the resolved force distance from the centre of the board. In other words, if the "rolling circle" radius is increased, the board will "drop" and rotate less before reaching its minimum potential energy resting position.

This means that the maximum board angle corresponding to each resolved force location along the board can be increased or decreased. The path of the trochoid minima for this situation can be plotted to show the "resting angle" of the board with respect to the resultant force location along the board, as shown in Figure 44. For ease, this path of trochoid minima will be referred to as the board's characteristic curve.

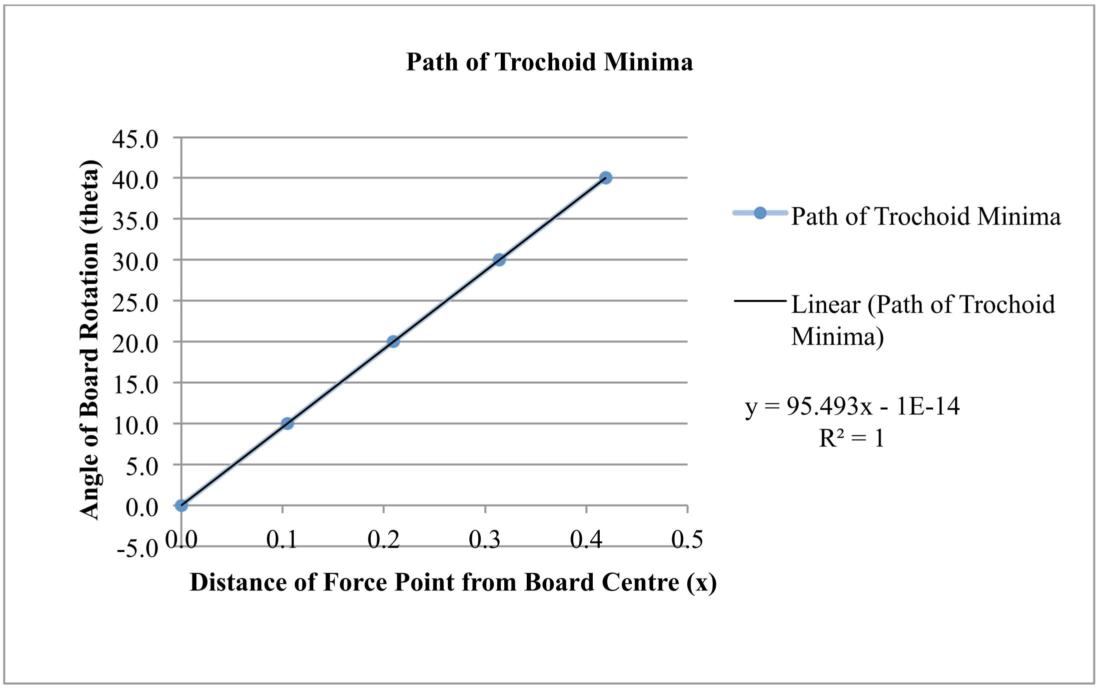


Figure 44: Characteristic Curve (or Path of Trochoid Minima) for Circular Rolling Surface

Since the roll distance of a straight object over a circle occurs linearly with respect to rotation angle, it makes sense that the characteristic curve is a straight line with a slope that can be changed by altering the radius of the rolling surface. This result is encouraging because it means that the rate at which the board rotates relative to the movement of the rider's force away from the board's centre can be increased or decreased as desired. This change can be achieved either by increasing the radius of the rolling surface, which would decrease the relative rate of rotation, or by decreasing the rolling surface radius, which would have the opposite effect.

Concept 6 was the first attempt at designing a practical mechanism that would simulate a rolling board motion. The behaviour of Concepts 2, 3 and 5 displayed some hesitation and "trochoid" point paths. However, the minima along those trochoid paths usually occurred too early and could not be readily changed by adjusting the dimensions since these linkages were not necessarily simulating a rolling board motion.

The rolling surface behaviour of Concept 6 was easy to adjust, which made it an ideal candidate for further analysis. The design and performance of Concept 6 will be explained in more detail in the following sections.

5.1.5 Board Stability Near the Centreline

Another important design specification for the Skiboard stipulated that the mechanism would benefit from having a region of stability near the tip-to-tail centreline of the board. At any point in this stability region, the rider can stand on the board and apply a downward force without causing the board or skis to tilt. It is necessary for the board to have this characteristic for the rider to maintain control of the Skiboard on downhill runs and while resting. An approximate range for the desired stability region was established with the assistance of the Skiboard/rider Excel model presented in Chapter 6. The final design specification reads: Stability 40 mm laterally about the centreline.

The earliest design concepts and prototypes of the Skiboard provided the rider with adequate stability near the centreline, but did not offer a gradual, controllable angulation outside of this region. The opposite problem was true of later models. The rolling circular surface model provides a board motion profile that satisfies the motion design criteria, but does not offer a region of stability near the centreline. If the resolved force of the rider moves to either side of the centreline, the point of the resolved force will begin to drop towards the circular surface and cause the board to tilt, as depicted in Figure 40 and Figure 42.

For the design of Concept 6, a region of stability was created by combining a function generation linkage with a motion generation linkage. The vertical lift provided by the former linkage overcame the initial drop of the tilting board, essentially forcing the system to remain at rest until the point of the rider's resolved force moved to a position at which the board's drop overcame the lift of the function linkage. Figure 45 illustrates the theoretical behaviour, or paths of motion, of several points along the board. The trochoids within the stability region (those appearing between the red arrows) experience an upward movement, against the direction of gravity, at the point of force application. Of course, the board will not follow these initially lifting trochoids as the rider cannot lift his or her own body weight by applying a downward force, resulting from their own body weight, without assistance.

Thus, in reality, the board will not tilt until the resolved force point moves outside of the stability range (or to the right of the second red arrow) where the start of that point's path of motion is in the direction of the applied force The effect is a “dead zone”, as shown between the red arrows. Along this region of the board, the application of force from the rider will not produce board translation or rotation. By designing the mechanism such that the lifting of the function generation linkage causes a small dead zone region, stability near the longitudinal centreline of the board is ensured.

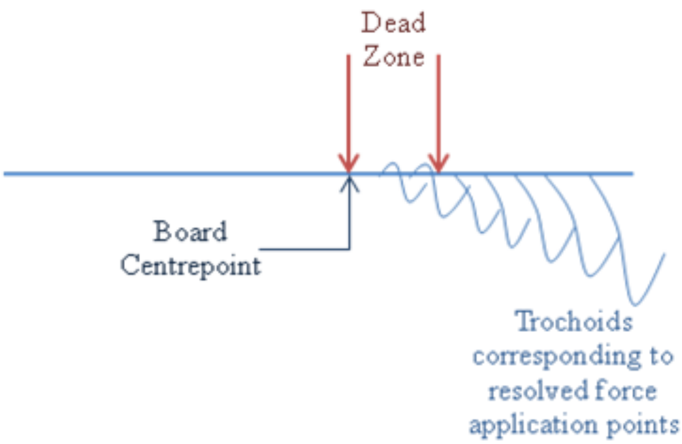


Figure 45: Rolling Board Behaviour with Function Linkage-Imposed Stability Region

5.1.6 Constraint - Horizontal Board Position

The final design specification was, perhaps, the most difficult to satisfy. This specification concerns the horizontal position of the board relative to the skis. For the system to remain stable, the position of the rider's resolved force must not be placed outside of the mechanism's stable base. In other words, the force vector must intersect the ground in the area between the skis. The evaluation of the forces in the system required a Skiboard/rider interaction model, as the rider's velocity and turn radius effect the angle of the force vector. Thus, they effect the location of its intersection with the ground.

Figure 46 shows an image from the rider model created in Excel. The yellow lines represent the directions of the force vectors from the rider's approximate centre of gravity. They terminate within the stable base of the Skiboard in this figure, which means that the rider will be stable under the tested conditions shown. These conditions represent a reasonable range of use as outlined in literature. (Howe 1983; David Lind 1996)

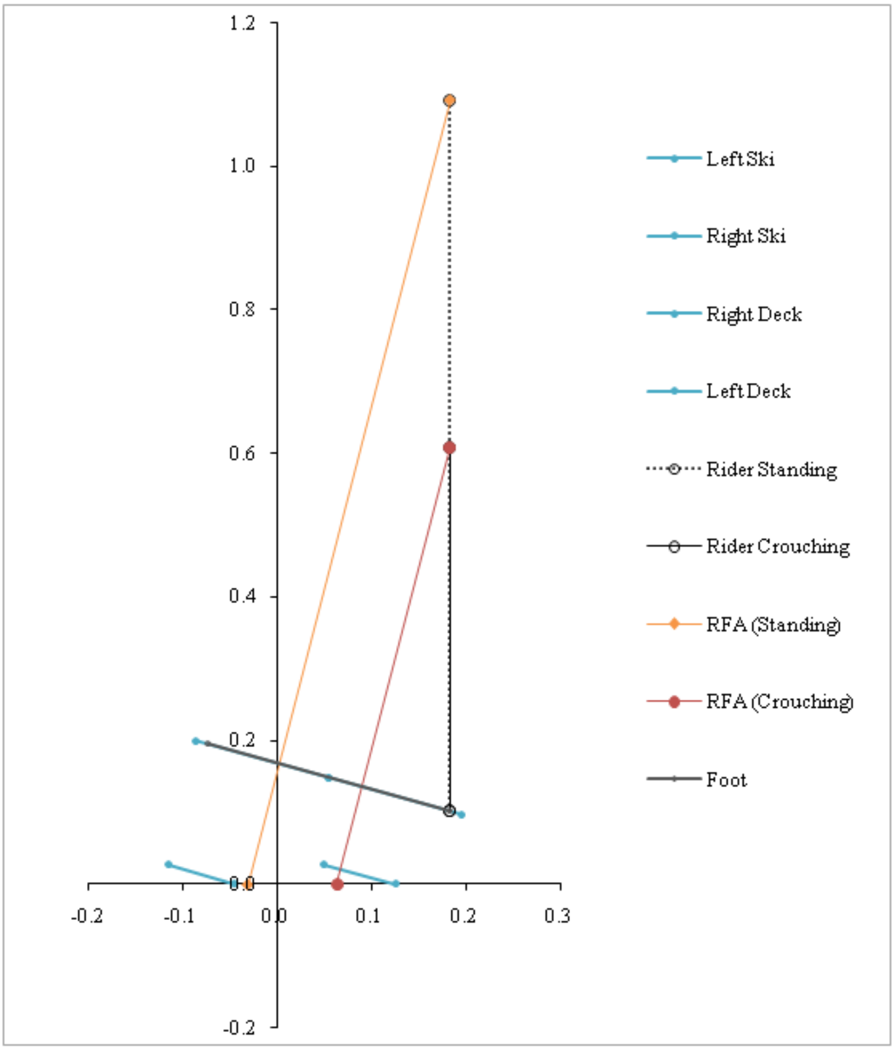


Figure 46: Rider Model from Excel

For any mechanism solution, the lift of the skis will naturally shift the board horizontally with respect to the skis. From the interaction model, it was established that the final design of the Skiboard would have to include a component or embedded behaviour to compensate for this natural horizontal shift. A rack and pinion type device could achieve this outcome, but would add a level of complexity to the final design.

Instead, for design Concepts 6 and 7, an upright support was added to limit the board's horizontal shift. A slider was added to the underside of the board to allow the link controlling the board tilt to slide along the board. The point of intersection between this link and the board can be considered the board's instantaneous centre of rotation. The trade-off involved in restricting the board's horizontal movement lies in the fact that it changes the board's motion profile. This effect and the concept of instantaneous rotation centres are explored further in the section that follows.

5.2 Pre-Production Concept 6

Concept 6 was obtained by combining two separate design solutions. One is for the function generation requirement and the other is for the motion generation requirement. These solutions are in addition to other links or devices necessary to satisfying the full range of design specifications. However, the combination of such components involves understanding the effect of their interactions and adds an iterative design step to the process.

5.2.1 Four-Bar Function Generator

The bottom half of the mechanism was designed to fulfil the function generation requirement. It is responsible for keeping the skis parallel and translating board angulation into ski angulation. The shape of the links used to construct the basic A-frame design were altered during the detail design phase to accommodate the positioning of the other links in the system and to avoid the collision of the skis and parts of the motion generation linkage with the frame, as shown in Figure 47. However, the functionality remained the same.

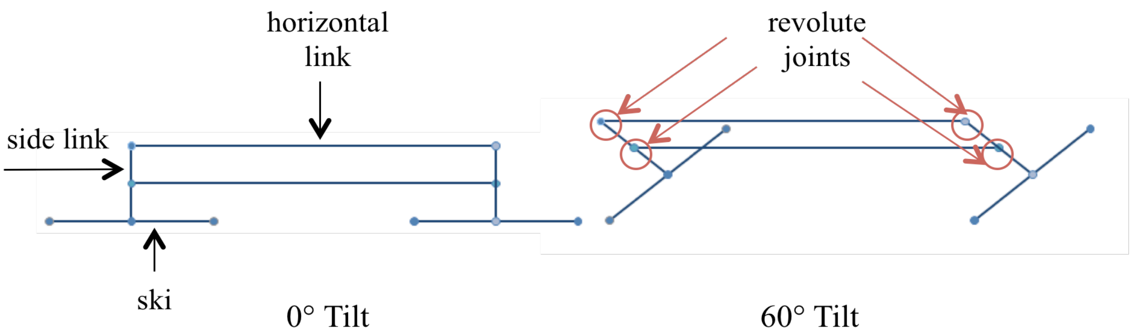


Figure 47: Four-Bar with Skis at 0° of tilt and 60° of tilt

Three independently variable dimensions of this four-bar mechanism were critical to establish. First, the length of the equal and parallel horizontal links impacts the stability of the system. If these links are too short, the rider's resolved force vector will easily topple the Skiboard by moving outside of the gap between the skis. If the horizontal links are made too long, the Skiboard will become large and clumsy.

The second dimension, the height of the side links, also influences the overall size and rider stability of the system. If the side links are too tall, the skis will not be able to tilt through their full range of motion (60-degrees) without the entire linkage being toppled over centre. Figure 48 illustrates this unstable four-bar linkage scenario in a case where the bottom horizontal link carried the applied load. This load is applied to the side link at the location of the arrow, shown below. This force component acts in the direction of gravity and the arrow representing it intersects the ground <u>outside</u> of the stable base.

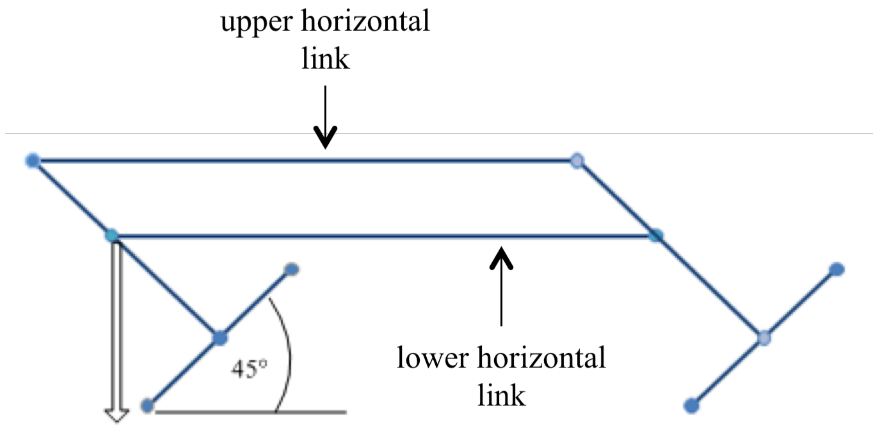


Figure 48: Unstable Function Generation Linkage

According to Hopper (Hopper 1973), "a rigid body standing on a base of finite size is 'stable' provided that the vertical line drawn through its centre of gravity passes within that base." Several preliminary concepts for the Skiboard linkage placed the applied load on the upper horizontal link rather than the lower one, but this mistake caused the models tested with COSMOSMotion to show evidence of having singularity issues.

The physics concept of a stable base is among the most basic concepts. However, it is one of many fundamental considerations that can be forgotten when the intense focus of the designer is placed on achieving a desired path of motion. Hence, intermittent reference to a design process is vitally important.

Returning to the discussion of the Skiboard, the separation distance between the horizontal links is the third crucial dimension to consider. Maximising the initial separation between the skis results is important in order to create a stable base for the system. The wider this stable base, the wider the range of horizontal movement and speeds at which the rider can stay balanced. This fact is illustrated in Chapter 6, where the impact of centripetal forces on the stability of the rider is discussed.

One limiting factor on maximising the initial separation of the skis is that the horizontal links could become very long. Since these long links will support the weight of the rider, the fact that longer links are more prone to bending must be considered. In addition, depending on the material chosen for the application, long links could add unnecessary weight to the system. Analysis of a kinetic model of the rider on the Skiboard, presented in Chapter 6, assisted the author in deciding upon the optimal length for the horizontal links, which directly determine the initial ski separation.

One of the most important functions of the four-bar function generation linkage is to control the gearing between the skis and the board. By adding a board attachment link between the top and bottom horizontal links on the four-bar, the angle of the skis can be directly translated to the board. To create a favourable gearing ratio between the board tilt and the tilt of the skis of approximately 1:1.2 (or 5:6 if expressed in an integer fashion), a coupler was added to the top link to decrease the board's degree of tilt with respect to the skis. Note that the coupler was eventually moved to the bottom link for the final version of Concept 6 to further increase the gearing ratio. The illustration in Figure 49, created in Blocks within SolidWorks, is a simple sketch showing the effect of adding a coupler to the top horizontal link. The gearing ratio can be directly controlled by changing the height of this coupler.

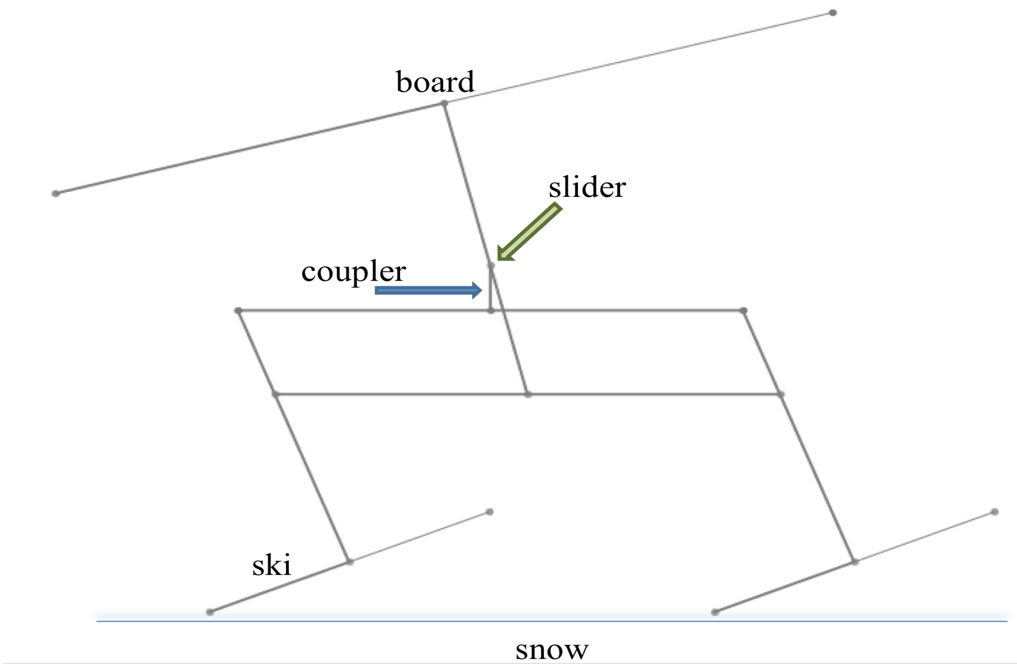


Figure 49: Blocks Sketch of Concept 6 - Gearing by Addition of a Coupler

5.2.2 Motion Generation Linkage

The top half of the mechanism, designed to fulfil the motion generation requirement, is responsible for guiding the board over a circular rolling surface or replicating this behaviour as precisely as possible. The design of this part of the mechanism began by analysing the motion requirements for the board support member, or the vertical link that would need to be placed perpendicular to the board to connect it to the rest of the system.

Using a model representing the circular rolling surface, a hypothetical path for the endpoint of this vertical support was plotted. By determining the desired point path for this part of the system, it was thought that a linkage could be found to generate this path, thereby satisfying the motion requirement in simple fashion.

If a board rolling over a theoretical circular surface has a support member secured to its underside, the endpoint of this support will trace a path that is nearly circular. The simple illustration in Figure 50 shows the board, with a rigidly attached support, tilting through several positions as it rolls over a simulated circular surface (not shown). A nearly circular path is traced by the board support as the deck "rolls" over the theoretical circular surface.

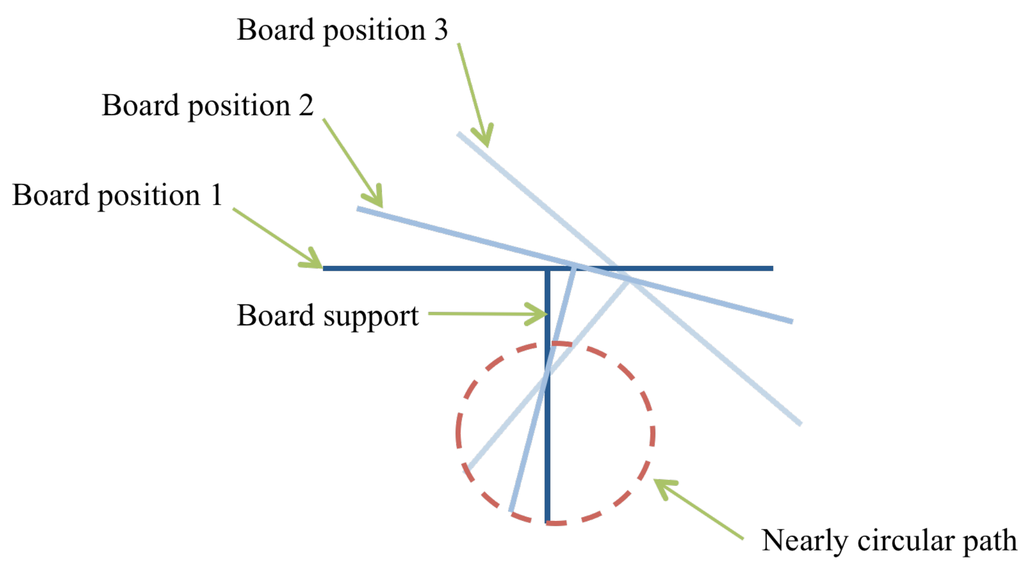


Figure 50: Illustration of Board Support Path

By recognising the relationship of this circular point path to the rolling behaviour of the board, the design problem is somewhat simplified. Of course, the diameter of the circular path traced by the support endpoint will change with changing support length. To put these concepts into perspective, Figure 51 shows a series of trochoids traced by a board (shown in two positions as blue dotted lines) attached to a support.

The path traced by the endpoint of the board support in Figure 51 depends on its length. Two different hypothetical board support lengths are shown, the shorter shown as a black dotted path below the board and the longer shown as a cyan dotted path below the board.

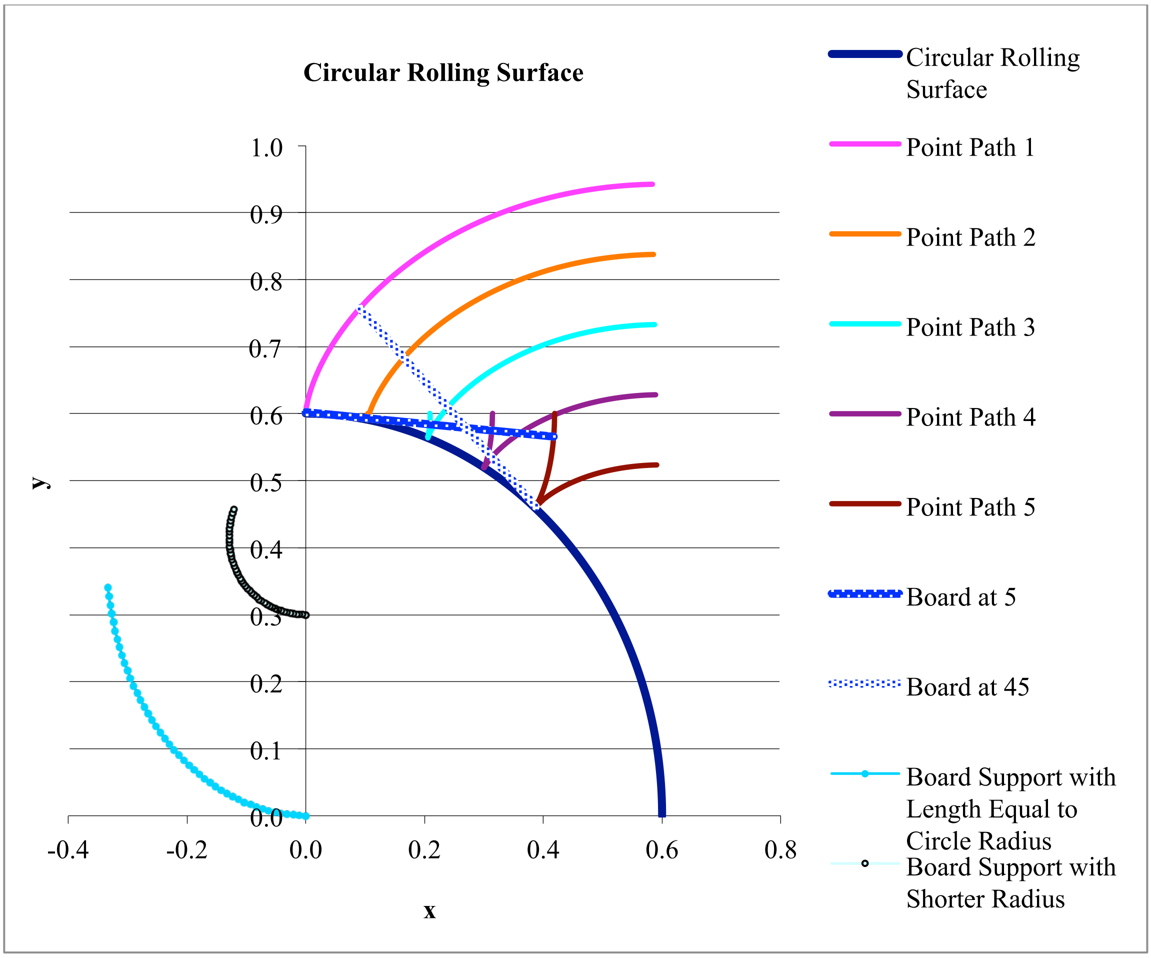


Figure 51: Actual Board Support Path Shown with Trochoids

During the design of the motion generation linkage, the need for this circular path of motion for the endpoint of the board support resulted in a simple design solution. The next step in the design process, to combine the function generation linkage, the motion generation linkage and the “constraint” link, presented its own unique design challenges.

5.2.3 Combined Solution

The dimensions of the linkage were altered and recombined using the SMAC program of Chapter 3. The COSMOSMotion image in Figure 52 shows the most favourable configuration designed. It presents the trochoid point paths shown in Section 5.2.2 while accomplishing the task of linking the board to the skis.

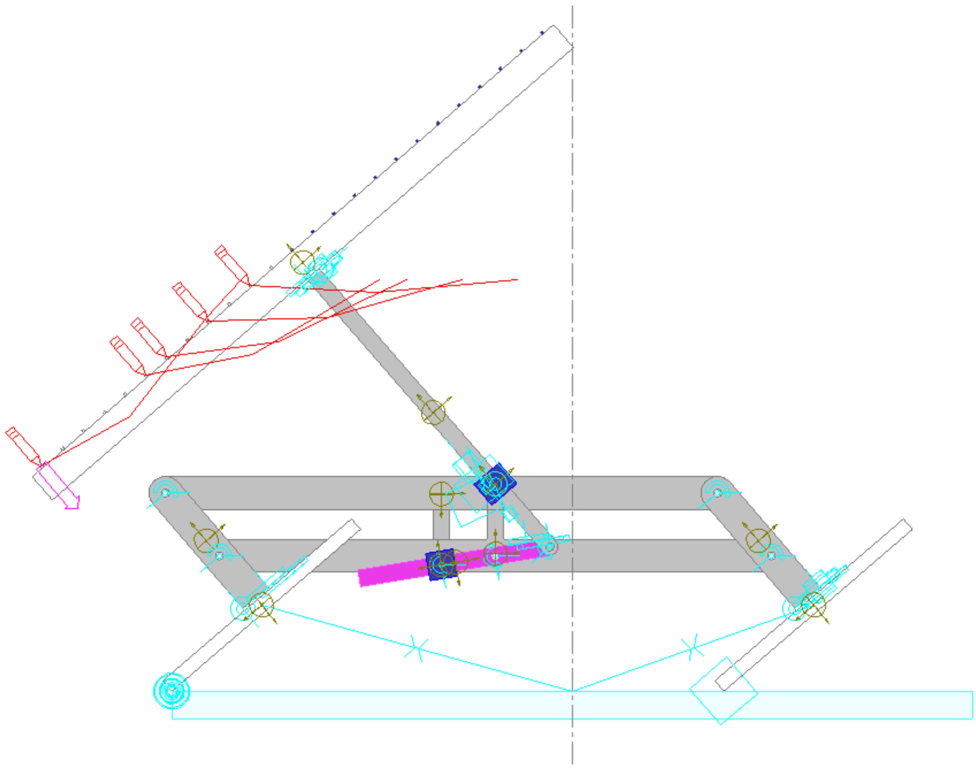


Figure 52: Concept 6 COSMOSMotion Screenshot – Configuration 6.3.7

While this configuration appears to meet the design specifications, a closer look at the output data in Excel reveals an undesirable characteristic curve. As Figure 53 reveals, the point paths along the board did contain local minima in the path of motion, indicating a reversal of the board's travel from descending to ascending. However, these minima occurred within just a few degrees of board tilt. This is important because the rider's range of motion would not be wide enough. The board would tilt to maximum in correspondence with the rider's position being very close to the centre.

Thus, motion and function generation components of this design met the design specifications independently. However, the combination of the two did not yield the desired overall behaviour. Although this concept did not perform as well as expected in preliminary testing, it was remodelled mathematically in Excel for three reasons.

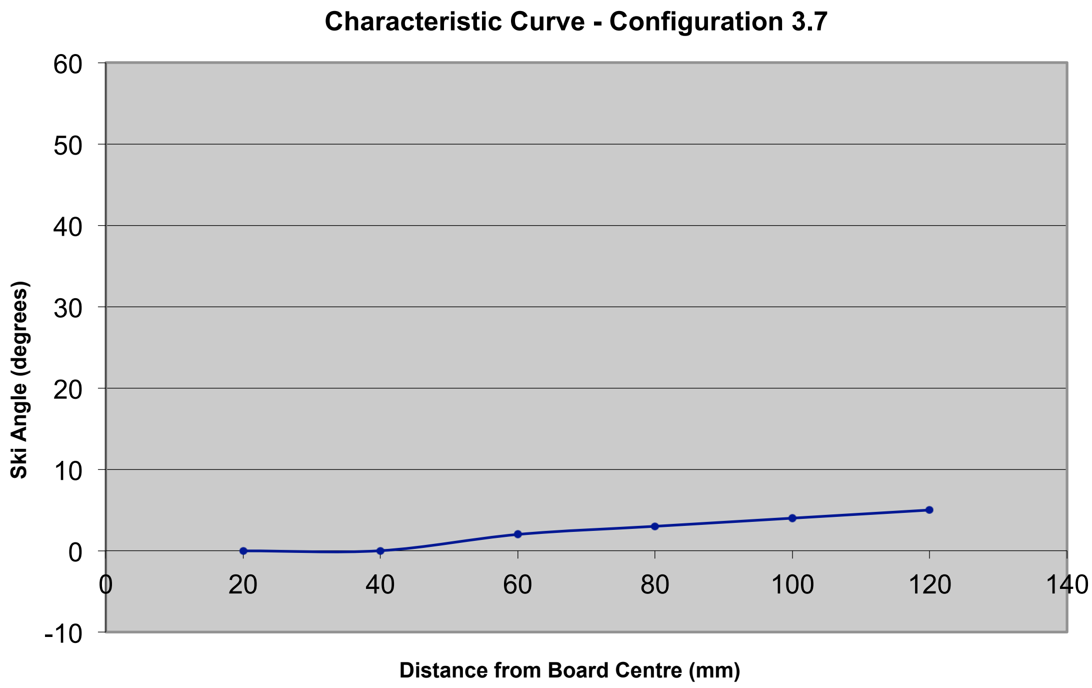


Figure 53: Ski Tilt Initiation Curve - Configuration 6.3.7

First, it was remodelled to validate the COSMOSMotion results. Second, since the point paths did contain local minima, it was thought to be worth using a more efficient tool to search for solutions that might exist outside the range of variables originally tested. In particular, adjusting variables within Excel is easier and more efficient than changing model dimensions in SolidWorks and allows the sampling of many more variable combinations. The third reason for remodelling was to create a framework for combining the Skiboard model and the model of the rider. While the PDS was modified to ensure the stability of the rider, the model of the forces on the rider needed to be added to the Skiboard model to verify the satisfaction of rider-related design requirements.

The Excel model confirmed the satisfaction of the rider-related requirements. However, it did not yield dimensional configurations that improved the characteristic curve of Concept 6. By separately evaluating the linkage components of the system, it was determined that the vertical lift provided by the function generation (four-bar) linkage caused the trochoids to prematurely reach their local minima.

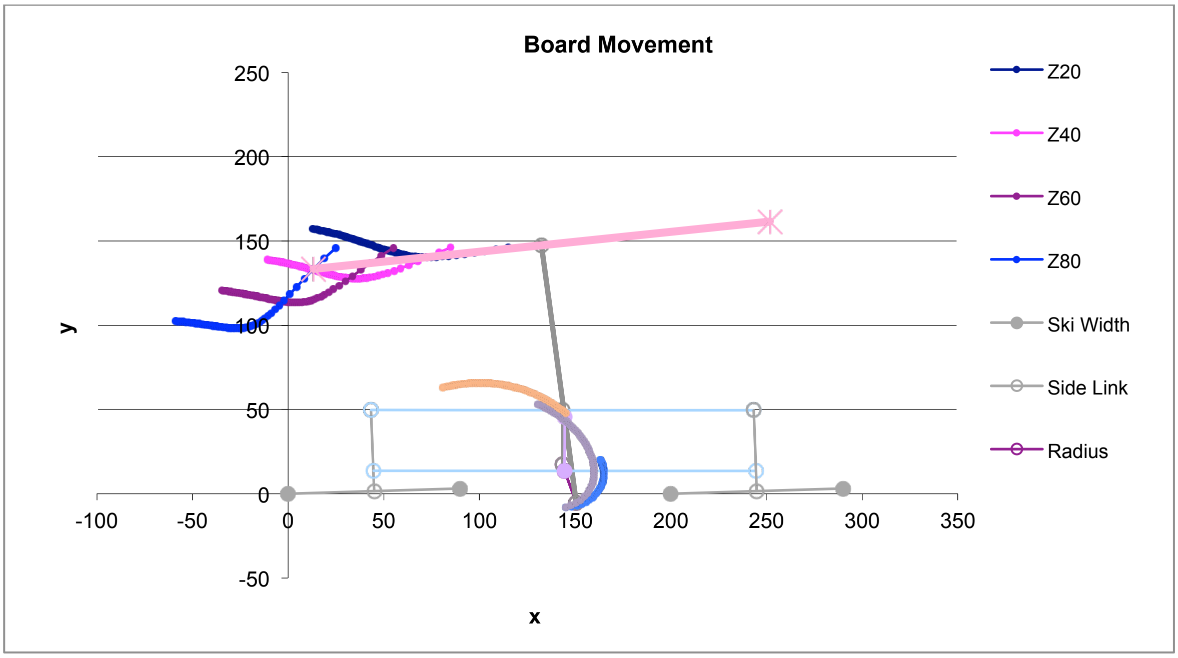


Figure 54: Concept 6 Test Results in Excel

Concept 6 was the first practical concept to satisfy most of the design specifications, but was not an optimal solution. It was considered for physical prototyping due to the presence of hesitation motion characteristics, as the effects of this behaviour were in need of physical validation. However, it was decided that a model that could offer a more pronounced and delayed hesitation would produce a more useful prototype in terms of testing the design specification theory.

The success of Concept 6 relative to previous solutions illustrates the benefits of breaking a complex design problem into its more easily solved components. It may lead, in future iterations of design, to a type of linkage mechanism that satisfies the hesitation requirements. However, for the purpose of physically testing the theory of hesitation, another type of design was chosen.

5.3 Pre-Production Concept 7

The design of the physical prototyping model involved the use of a cam, as the shape of the cam profile would be easy to control and would ensure that the prototype met the motion and function requirements in computer simulations for eventual physical validation. Originally, cams were discounted as possible design solutions due to high manufacturing costs, high dimensional tolerances and poor wear characteristics. (Uicker, Pennock et al. 2003). While these characteristics still make cams unsuitable for a final design solution, they were employed to quickly produce a satisfactory physical testing prototype to inform future design concepts. It was recognised that further computer simulation without physical validation would be unwise, as physical prototyping, especially where mechanism design is concerned, is a particularly valuable and vital part of the design process.

One of the most profound benefits of using a cam profile for this prototype model is that the profile has the ability to be designed such that it exactly compensates for the lifting action of the function generation. The path of motion for any component, or point on any component that is attached to the board can thus be specified and synthesised with respect to the ground. It is easily synthesised because the cam essentially subtracts the motion of the underlying four-bar mechanism.

The cam follower was attached to the upright board support in a similar fashion to its attachment to the coupler in the Concept 6 model. The exact profile of the cam follower was obtained by using an Excel model of the Skiboard similar to the one mentioned in the previous section. Using this model, the desired motion profile of the board and functional behaviour between the skis and the board were specified and a corresponding cam profile curve was obtained.

5.3.1 Board Motion Generation

For Concept 7, the problem of creating an imaginary rolling surface for the board was solved differently than for Concept 6. As discussed in the previous section, the board's rolling motion was created by constraining the endpoint of the board support member to follow a circular path. The motion generation component of the Concept 7 model was created by constraining the centre of the board itself to follow a circular path and shifting the "rolling centre", such that it always remained in contact with the imaginary rolling surface. This concept is illustrated in Figure 55.

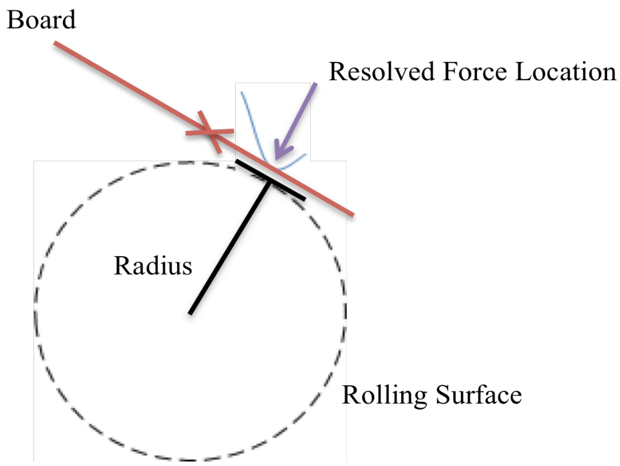


Figure 55: Rolling Surface and Sliding Board

The radius, which follows the circular rolling surface, is attached to a surface that supports the underside of the board. This attachment is positioned directly beneath the centrepoint of the board when the system is at rest. As the radius follows the path, the board above it slides until the resolved force location aligns with the trough of its corresponding trochoid. At this point, it will temporarily be at rest.

By generating rotation and backwards slide, the motion generation problem can be solved. The problem of creating a practical embodiment of this solution was divided into two tasks. The first deals with constraining the board centre to follow a circular path, with respect to the ground. The second concerns shifting the board such that the instantaneous centre of rotation moves to follow the circular path.

5.3.1.1 Circular Board Path and the Zero-Point Theory

From the experiments with Concept 6, it became clear that Concept 7 should be designed so that the board is constrained to follow a circular path with respect to the ground, taking into account that the four-bar linkage responsible for the function generation will lift the entire system. To ensure that the cam follower would meet this requirement, the concept of a zero-point path was introduced. The idea behind this concept is that the endpoint of the board pivot radius follows a straight line path with respect to the ground as the board tilts, always with this point as its centre.

The x, y coordinates of the points comprising this path are found by selecting any y-value along the collapsing portion of the link supporting the board, also referred to as the board radius, and locating the corresponding progression of x-points through the range of motion of the system. Note that the length of the radius of the rotating board, from the zero point line to the effective board centre, remains constant. Note also, the range of motion of the system refers to its degree-by-degree ski tilt from minimum to maximum ski angulation. Since the four-bar linkage is the only linkage component of the system moving the board's radius endpoint horizontally, this linkage is responsible for determining the x-coordinates of the zero-point path. This virtual zero-point path is shown as a dark blue line in Figure 56.

The connection between the upright board support and the cam profile necessitates the collapse of the support link between the cam profile, which is placed on the upper horizontal cross link, and the lower horizontal cross link. Figure 56 contains a graph showing the paths of various points in the system. The path representing the cam profile that was calculated by the program is labelled accordingly. The cam profile developed in Excel was exported to SolidWorks as a text file so that the profile could be cut into the upper horizontal cross link to a depth that would fit a cam follower.

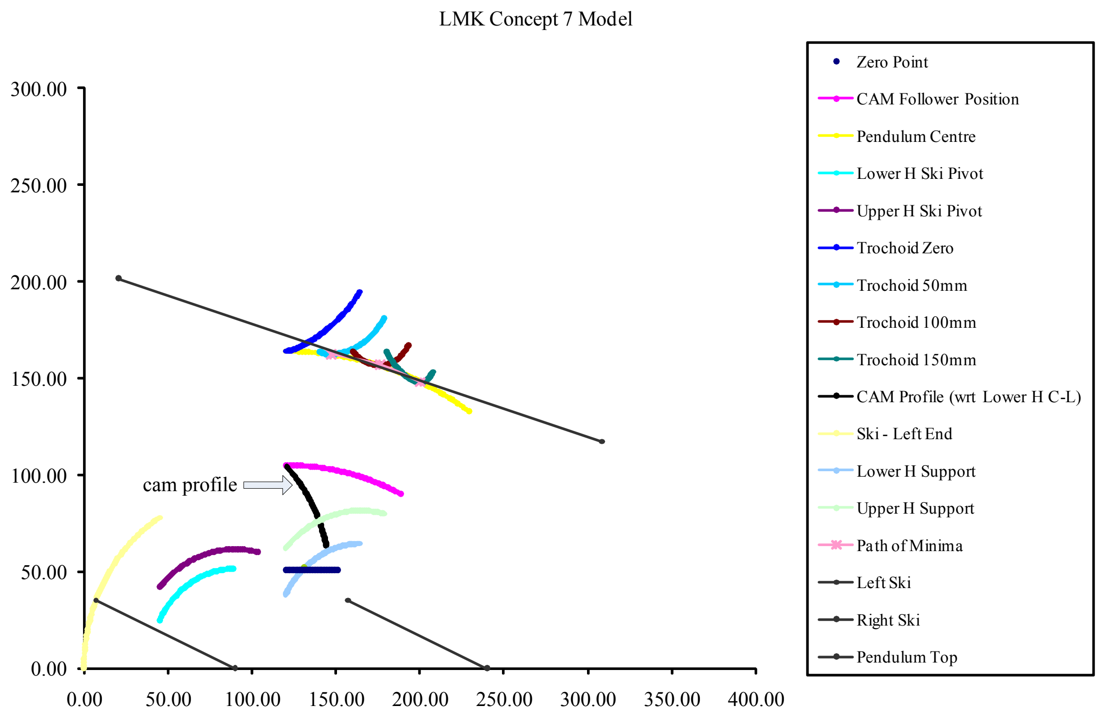


Figure 56: Concept 7 Cam Profile

5.3.1.2 The Importance of Frame of Reference

It is important to explain at this stage that for this design concept, as well as for the concepts that follow, the board's theoretical rolling surface is circular only with respect to the underlying function generator, which is the four-bar linkage that makes contact with the ground. With respect to the ground, this rolling surface is not circular. This disparity highlights the importance of combining candidate solutions for separate parts of a design problem to observe the interaction effects.

The horizontal, or x-direction, movement of the four-bar linkage essentially “stretches” the rolling surface with respect to the ground so that it resembles an ellipse more than a circle. While this difference was unexpected when the function and motion generation linkages were being considered separately, it did not introduce ill effects. Rather, this new board motion was found to be a more desirable solution than the circular rolling surface. The benefit of rolling the board along an elliptical surface lies in the fact that it effectively delays the hesitation points or trochoid minima. In other words, the normally hook-shaped trochoids would be stretched along with the rolling surface. The theoretical effect of this can be seen in Figure 57.

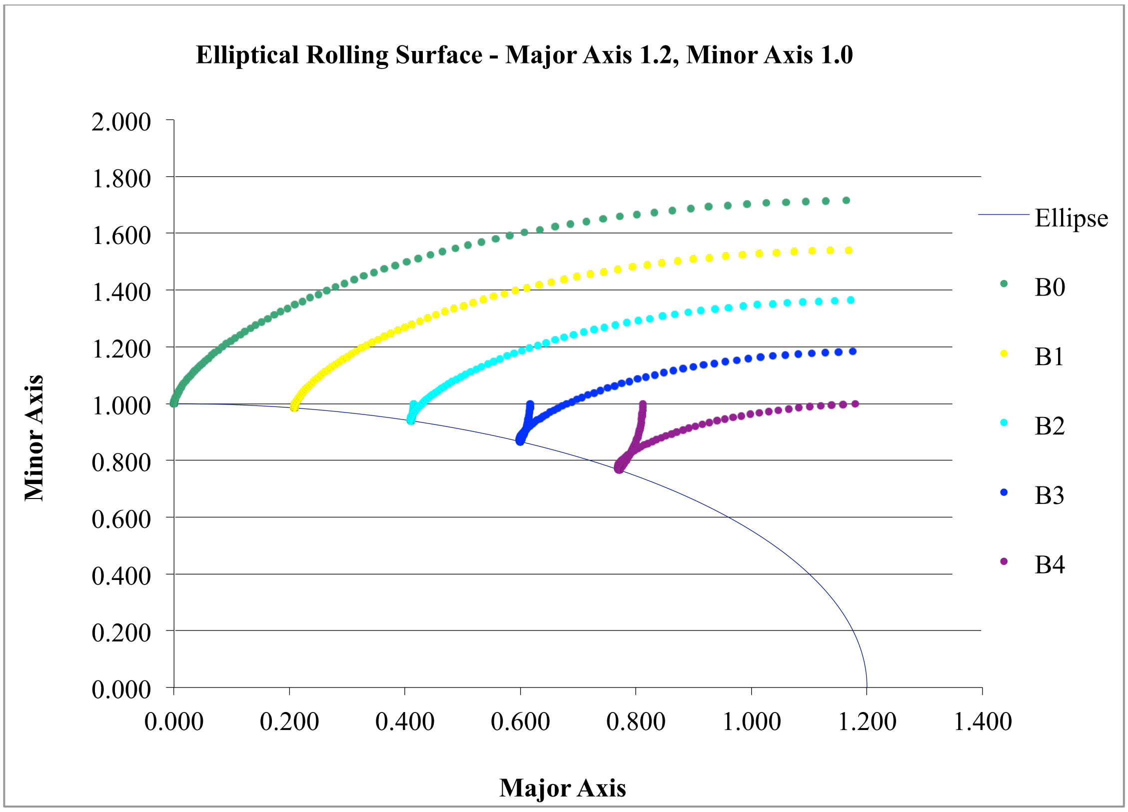


Figure 57: Elliptical Rolling Surface

This behaviour is desirable for two reasons. First, it remains satisfactory with regard to the design specifications because it gradually tilts the board and produces a favourable characteristic curve. Second, it is desirable because it provides added stability and control near the centre of the board in comparison to the circular rolling surface. In this case, the combination of the coordinated motion components led to an enhanced understanding of the board motion requirements and improved satisfaction of the specifications.

For the remainder of this chapter, the rolling surface of the board will usually be referred to as circular in shape because it will be modified within the frame of reference of the motion generation link. However, it is worth noting that the shape of this rolling surface with respect to the ground and in the final analysis of the performance of the design concepts will be elliptical.

5.3.1.3 Instantaneous Centre of Board Rotation

Each trochoid minimum corresponds to an instantaneous centre position. This instantaneous centre of the board's location occurs that the point of resolved force application. For the Concept 7 model, it was necessary to shift the board as its absolute centre was guided along a circular path. This shift needed to occur such that the resultant force point intersects the imaginary rolling surface, thus creating a position of stability. In other words, it was necessary for the intersection point of the board's radius and the imaginary circular rolling surface to become the contact point for the board's corresponding trochoid minimum location.

Despite the complex nature of the concept, the behaviour was relatively easy to implement physically due to the fact that the distance travelled by rolling board is equal to the arc length of the radial distance travelled. This relationship is linear and can be easily determined by establishing the length of the board radius. Concisely stated, the board radius variable directly impacts hesitation behaviour and can be manipulated easily to produce this characteristic.

The method of implementing a linear “backward” sliding of the board presented some practical challenges. Since this concept was meant for immediate physical prototyping, rather than for concept testing, the design solution needed to be easy and practical to manufacture without requiring cycles of design iterations. A rack and pinion device presented itself as a natural design solution to a problem requiring linear slide. However, such a device would be expensive to implement and could present the problem of racking since it would experience the maximum compressive loading applied to the system. Hence, a simpler option was explored.

This simplified device restrained the “resting centre” of the board, or the original centrepoint of the board when its angle of tilt is zero, horizontally with respect to the four-bar linkage, allowing the radius to slide along the width of the board. This point was restrained by a vertical up-stand that was attached to one of the horizontal links on the four-bar linkage. The board’s resting centre was pinned to this restraining link to allow rotation, but prevent sliding. The radius link below the board was attached to sliders so that it would have the freedom to slide smoothly beneath the board and control its angle of tilt. This part of the mechanism is shown in Figure 58.

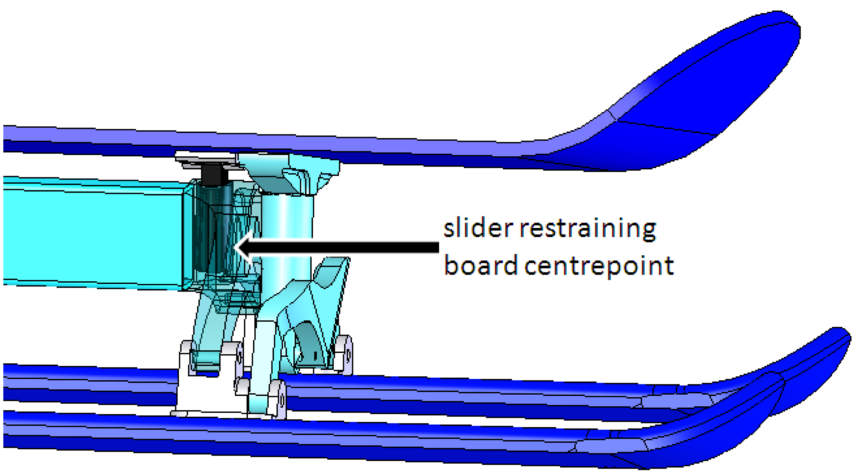


Figure 58: Concept 7 Model

This upright link, in addition to creating a “backwards” sliding action, also serves the purpose of keeping the board centred and, as a result, the forces, between the skis and within the limits of the stable base of the system. Initially, the drawback to using this solution to slide the board was the fact that it does not slide the board in a linear fashion. Figure 59 is a model of the incremental board sliding distance.

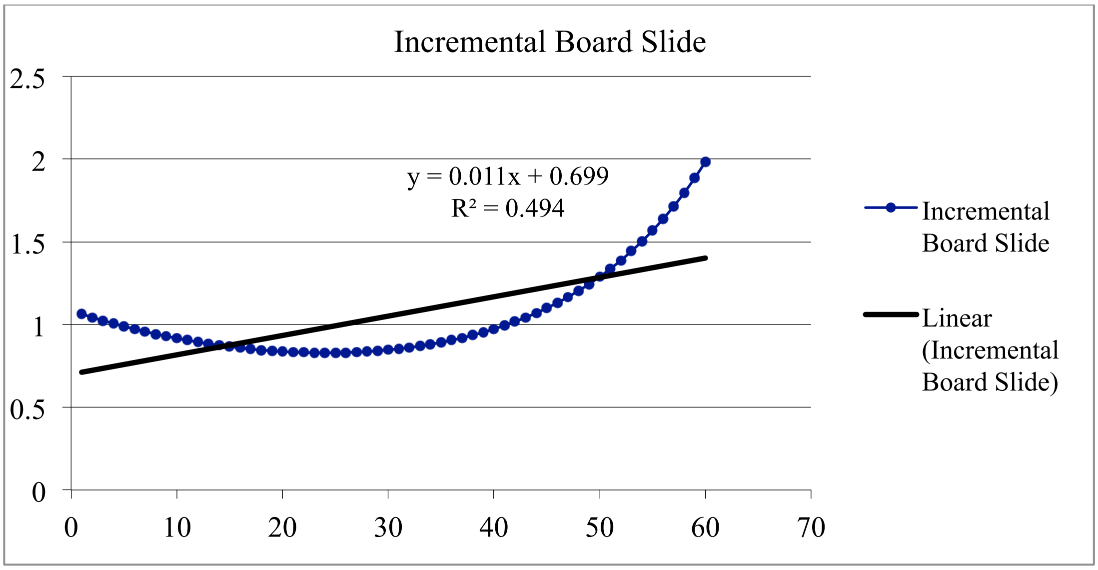


Figure 59: Incremental Board Slide from Upright Centrepoint Restraint

The reader may recall from Figure 44 that the roll distance travelled by the board over a circular surface is linear. Thus, the only way to achieve the exact trochoid paths associated with the circular rolling surface in this case is to impose a linear “slide back”. Fortunately, upon inspection of the cumulative effect of the upright support system on the amount of board slide, it was observed that the board would, in fact, slide back in a nearly linear fashion, as shown in Figure 60.

Linkage components for the function generator and motion generator along with the board restraint/slider mechanism were combined to form Concept 7. Testing in SMAC confirmed that the combination of these components produced favourable behaviour.

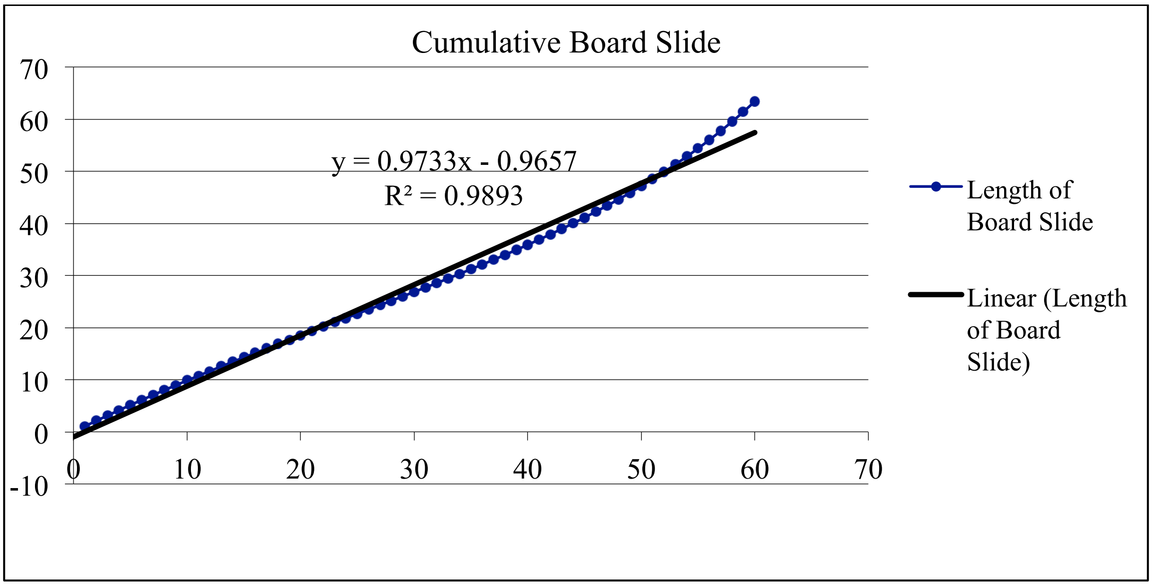


Figure 60: Cumulative Board Slide from Upright Centrepoint Restraint

According to the available assessment tools and criteria, Concept 7 met all product design specifications, design constraints and force-related constraints. It was moved towards the physical prototyping phase of the design process and technical drawings were produced. Basic Design for Manufacture (DFM) principles were applied for the manufacture of the prototype since the system required high manufacturing accuracy. As the components were required to interlink with tight clearances and operate in the small space between the skis and the board, strict space constraints were placed on the design which also necessitated employing DFM principles. The task of manufacturing this concept will be discussed as future work in Chapter 7.

5.4 Conclusion

The design process for the Skiboard linkage took the design through eight phases of iteration and experimental testing. Interaction with the models and experimental results informed the product design specifications which resulted in a more refined understanding of the motion and size requirements of the linkage. With this deepened understanding, to concept of creating a virtual rolling surface was developed.

Concepts 6 and 7 embodied the rolling surface solution. Concept 7 was chosen for future prototyping. Accordingly, engineering drawings of a complete assembly were made using DFM principles. These drawings are contained in Appendix E.

Chapter 6.

Forces and Anthropometric Mathematical Modelling

In the case of the Skiboard, establishing a specific motion generation requirement for the board involved ensuring that the board's motion would provide stability for the rider under typical riding conditions. The human interface aspect placed constraints on the motion and size of the Skiboard, adding another layer of complexity to the design process. Such is the case with many design tasks, as the majority of mechanical systems must be designed with the human user's needs in mind.

People can be particularly difficult to design for due to the range of variability in mass, proportions and style of product use. Assumptions must be made by the designer as to how the person will interact with the mechanical system. Anthropometric data is readily available to aid the designer in evaluating the constraints human interaction will place on the functional requirements as well as other performance-based and structural characteristics. (Floyd 2007; Grimshaw 2007)

Since human constraint modelling is one of several critical constraint definition tasks involved in the mechanism synthesis process, it is preferable to choose constraint-modelling programs are compatible. Therefore, the analysis of biomechanics for the Skiboard was performed in Microsoft Excel due to its compatibility with the rest of the experimental setup. This chapter includes a description of the constraint-modelling process that was carried out to determine the effect of human factors (forces, stance on the board, etc.) on the design requirements and to analyse the fitness of design solutions.

6.1 Forces on the Rider

One of the goals of this project was to optimise the system, meaning the mechanism and its interaction with the rider and the surrounding environment, according to the biomechanics of the rider. Models of the forces acting on the rider were created to analyse the rider's range of stability with respect to Skiboard dimensions and movement. The factors influencing the magnitude and direction of these forces include the position of the rider's centre of gravity and riding conditions such as speed and turning radius. Gravitational forces on the body and comfortable riding position were also taken into consideration in the models.

6.1.1 Stability Analysis

In this case, the difference between stability and instability is the difference between staying on the board and falling off. It is assumed that the stability of a rider in a turn will be influenced by the location of the rider's centre of gravity with respect to the stable base (the skis). The effects of centripetal force and friction will also impact stability. This discussion of stability will begin with the description of all of the major forces acting on the rider and why each of them was or was not accounted for in the model.

The first, and most obvious, force acting on the rider is gravity. Figure 61 shows the line of the rider's gravitational force, or weight, acting through the rider's centre of gravity (CG), also known as the centre of mass. This figure shows three different force situations.

In the first case, the rider's gravitational force passes between the edges of the skis, or through the "stable base" as termed by Hopper (1973). In this case, the rider's weight is not applied entirely to one ski, so the board will not topple. Therefore, the rider's situation is said to be stable.

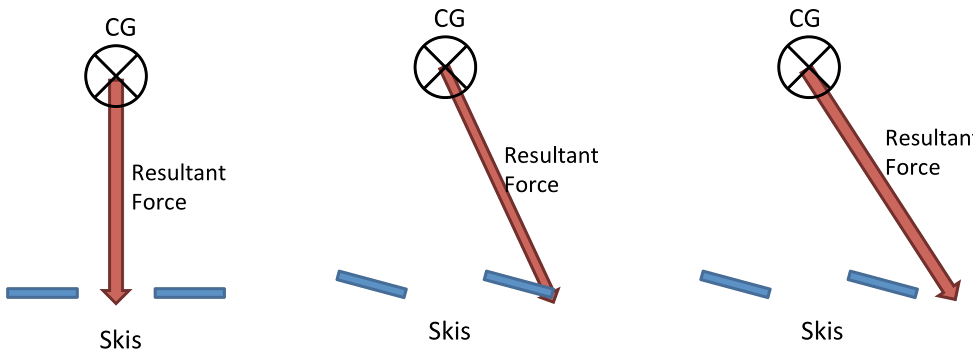


Figure 61: Resultant Force Directions

In the second situation, the rider's force is directed over the edge of the ski, which produces a singular position. This circumstance is unstable and should be avoided. The third case shows the rider's force well outside the stable base, which is sure to result in the topping of the Skiboard. In this case, the rider is unstable.

The introduction of centripetal force changes the direction and magnitude of the force acting through the rider's centre of gravity, CG_r, and can make a statically unstable situation dynamically stable. Centripetal force is the result of the rider's momentum travelling radially. The relationship between centripetal force, F_c, the rider's mass, m_r, the rider's velocity, v_r and the turn radius he is traversing, r, is expressed by Equation 4.

Equation 4

$$F_c = m_r * v_r^2 / r$$

Centripetal force acts perpendicular to the ground from the rider's centre of gravity, as shown in Figure 62. The addition of the centripetal force vector, F_c, and the rider's gravitational normal force vector, F_N, produces a resultant force represented by the vector labelled F_{load}. The addition of centripetal force moves the resultant force through the rider closer to the stable base, which explains why the skier in the figure is able to lean more severely when travelling at speed than when standing still.

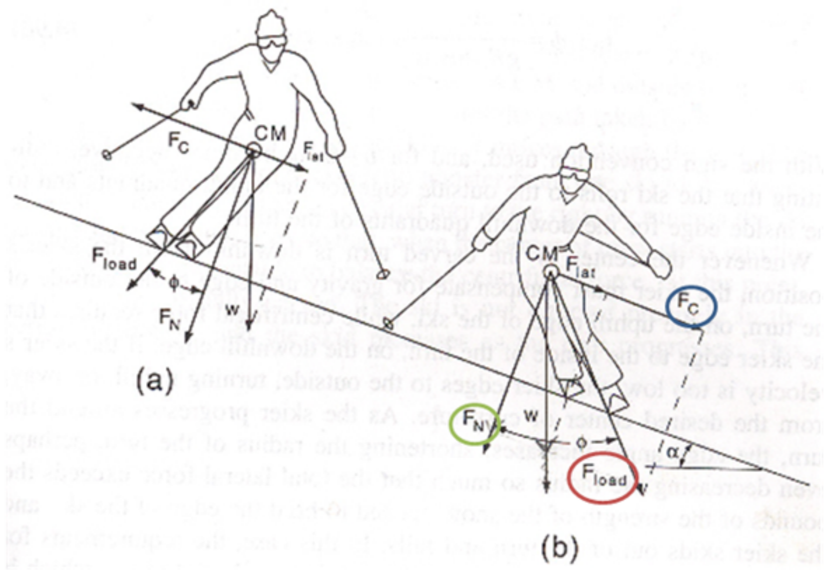


Figure 62: Skier Force Diagram (Lind 1996)

The forces that have been accounted for in this stability model are gravitational and centripetal. Frictional forces have not been modelled due to the variability of frictional coefficients. Coefficients of friction are influenced by the material of the board covering (which has not yet been chosen or designed), the material of the footwear and the presence of snow, ice, water or grit. Since these forces are difficult to predict, they were not accounted for in this model.

To compensate for the absence of friction in the model, the rider's stability was assessed by evaluating an additional factor: whether or not the resultant force passed through the rider's stable base, which, in this case, is the rider's foot. In a real world situation, the force line could pass outside the line of the foot and the rider would still be held to the board by friction. However, since friction is not a factor that has been considered here, this through-the-foot condition is placed on the stability evaluation to ensure that the effects of friction are not overestimated.

The forces internal to the mechanism, such as the forces on each of the links and joints, were not accounted for in this model since its goal is to evaluate rider stability. The consideration of these forces was done using COSMOSMotion. A more in-depth internal force analysis will be required in future stages of Skiboard design to ensure robust manufacturing.

The position of the rider's centre of gravity, which has been taken as a given in this section, was estimated by considering anthropometrics and riding style. The location of this point will be discussed in the following section.

6.2 Rider Centre of Gravity Position

In extreme turns, the ability of the rider to stay standing will largely be determined by his or her sense of balance, strength and joint flexibility, much more so than if the same rider were on skis or a snowboard. In fact, the body movements of a Skiboarder are most similar to those of a skateboarder. For this reason, the biomechanics of skateboarders was researched in addition to the biomechanics of skiers.

In a paper by Wisse and Schwab (2005) the rider is modelled as an inverse pendulum, or point mass located at the centre of gravity. Thus, the model for the Skiboarder has been produced using the same consideration. The centre of gravity is taken to be a point mass with all forces on the rider acting through this point.

The movement of the rider's centre of gravity in the y-direction depends on body position and is difficult to predict. However, a range of possible locations can be modelled based on anthropometric data. (Hopper 1973) The standard equation for the height of a person's standing centre of gravity is shown as Equation 5.

Equation 5: Y-Position of Standing Centre of Gravity

$$y_{CG} = 0.55 * height_{rider}$$

A minimum y-position location was determined for a rider with knees bent. The y-position of this adjusted centre of gravity is estimated to be 28.2% of the rider's height. The range of centre of gravity heights between the standing and crouching values was determined to be the approximate range of motion of an active rider.

6.3 Board & Rider Interaction Model

Using anthropometric data, a model of the interaction between the rider and the Skiboard was created in Microsoft Excel. Excel was chosen over other software due to its compatibility with other programs being used for this research, namely Visual Basic and SolidWorks. With Excel, a simple board and rider interaction model was created to ensure that forces, dynamics and human anthropometrics could be accounted for during the design process.

6.3.1 Software Environment

In the human model, input variables are ski dimensions (such as side cut), overall rider dimensions, rider weight, potential extremes of riding conditions such as minimum turn radius and maximum velocity. The output of the model is the range of rider stability for a suggested path of motion, ski separation and overall height. A screenshot of the interface is shown in Figure 63.

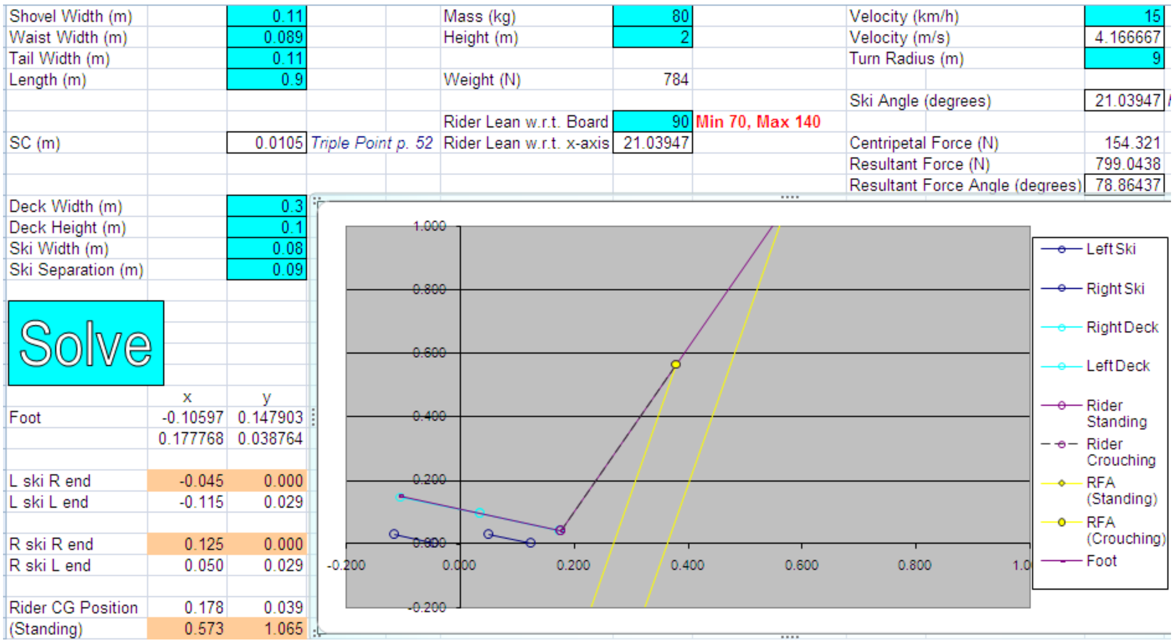


Figure 63: Rider Model User Interface

6.3.2 Refinement of Design Specifications

The human model introduced in this chapter is important in assessing the feasibility of a design. As with any design task involving direct user interaction, it is vital to consider the impact of forces on the human user and the corresponding levels of product usability, personal satisfaction and personal safety. Since the response of the human user is impossible to accurately predict, it is useful to assess the range of possibilities, especially the potential user response in an extreme usage situation.

In the case of the Skiboard a critical assumption is made in assessing the suitability of a design for the human user. According to this assumption, the design is a feasible solution if the rider has the potential to stay on the board under a relatively extreme set of riding conditions (tight turn radius combined with high speed). Extreme values for the variables of turn radius and speed were estimated to be just below racing speed. It is assumed that an extreme high speed for an apparatus with no bindings would be approximately 65 kph.

6.3.3 Refinement of Design Constraints

The design specifications were refined after performing virtual experiments with the rider model. These specifications are shown in Table 5. The most notable change to the PDS from the human model results is the addition of a maximum board height. The model shows that the rider's stability is particularly sensitive to the height of the board from the ground.

Table 5: Refined PDS

Function
Skis always parallel and laterally stationary relative to each other
Board to skis gearing ratio between 1:1 and 3:4
60-degree maximum ski tilt
Horizontal position of board centre within bounds of space between skis
Motion
Stability 40 mm laterally about the centerline
Elliptical rolling surface
Rolling surface radius approximately 100 mm
Motion behaviour force-independent (as defined by rolling path trochoids)
Other Constraints
Planar linkage
Maximum vertical distance between board & skis 165 mm
Few moving parts
Horizontal position of board centre within bounds of space between skis

Another constraint contributed to the PDS via human model experimentation is the requirement that the horizontal position of the board centre remains within the bounds of the skis throughout the range of movement. In other words, if a vertical line cannot be drawn from the board centre to the space between the skis, the Skiboard will not be stable enough for the rider to stay on the board. The model informed this constraint as well as several others, including rolling surface radius and board-to-ski gearing ratio.

6.4 Conclusion

The human model created for this design task informed the design specifications and aided in understanding the interaction between the design, the human variables and the forces on the system. The model, while simplistic, was useful in putting dimensional constraints on the height and range of motion of the mechanism. Several candidate mechanisms were tested using this model to ensure their feasibility for practical use.

The results from the human model testing were obtained manually. In future, however, it is hoped that this type of model can be integrated into a mechanism synthesis package using parametric models, such as PSEO. Since designing for human use is a relevant consideration for most mechanism design problems, models containing human anthropometric and force-related information would be useful in the assessment of design suitability.

Chapter 7.

Conclusions & Future Work

The design work on the Skiboard during this research yielded a deeper understanding of the motion and path requirements of a linkage solution for this complex design problem. While there are prototyping and development phases to be completed beyond the scope of this work, the solution concept chosen for future prototyping produced outcomes closer to a desirable solution than those of any previous concepts.

Most importantly, useful design methodologies and software tools were developed to assist mechanism designers faced with challenging, under-constrained design tasks like the Skiboard. These methodologies, SMAC and PSEO, offer new approaches to integrating the benefits of graphical and experimental synthesis with computer software. Both programs involve an element of automation, but preserve an interactive user interface.

In addition to developing a novel mechanism design methodology and design software concepts, this research has begun the task of compiling and summarising information from fifty years' worth of research in the field of mechanism design and optimisation. In particular, the works cited address the task of solving relatively under-defined, "black-box" linkage synthesis problems and design problems involving complex, multi-loop linkages.

This chapter will first explore the achievements relating to the Skiboard, followed by the developments made in the area of mechanism design research software tools. Future work as it relates to both of these aspects of the research is discussed in Sections 7.2.1 and 7.2.2.

7.1 Research Achievements

Several significant achievements were made in the course of this research, first with regard to the development of the Skiboard. The product design specifications, under-defined and largely qualitative at the outset of this research, were refined and, many of them qualified through research, modelling and testing. Human model results informed the overall maximum dimensions and angle of deck tilt for the Skiboard.

The concept of involute curves was adopted as a crucial design specification. These curves translated the qualitative requirement of a gradual, resistive tilt into quantitative terms. They also lent themselves to being synthesised via a linkage that produces a simulated rolling surface.

With the refined specifications, several potential solutions were created and sketched. Six of these concepts are discussed explicitly in this thesis. These concepts were tested using the SMAC program until a solution, Concept 7, generated the kinematic outcomes required in the PDS. The dimensions of this chosen solution were then optimised and the concept was modelled for manufacture.

Achievements were also made in the broader field of complex linkage synthesis, especially in the emerging area of experimental synthesis. A novel concept for experimentation and atlasing using 3D models, SMAC, was introduced and used successfully in designing linkages for the Skiboard.

A more advanced experimentation, atlasing and synthesis/optimisation tool, called PSEO, was also introduced at the concept level. PSEO takes a novel approach to integrating automation and sketching-based designer iteration. It employs a combination of the most easily-applicable, least mathematics-intensive synthesis techniques, namely graphical synthesis, atlas building and guided experimentation.

Through the use of a genetic algorithm, the PSEO concept automates the experimentation phase of design without entirely removing the user from the process. Linkage concepts are expressed in a visually-meaningful way, while also containing the appropriate topological, dimensional and constraint-related information. The analysis of solution fitness, an arduous process if done by hand, is also automated and delegated to a correlation algorithm that is based on computer vision principles. In these ways, PSEO aims to maximise the benefits of applying computer automation to linkage synthesis tasks.

7.2 Future Work

7.2.1 Skiboard Future Development

As the Skiboard linkage is a complex, multi-loop linkage, it will be vital in future stages of Skiboard development to check for occurrences of singularity through the desired range of motion. While information from COSMOSMotion has indicated the potential viability of the solution chosen for testing, physical prototyping results will provide necessary validation of the force-related behaviour of the Skiboard linkage design. Complete drawings have been created for the purpose of physical prototyping and testing.

7.2.2 Future Development of Mechanism Synthesis Tools

As briefly discussed in the chapter on PSEO, the trend in linkage synthesis software in recent years has been towards automation and fast, efficient synthesis methods that enable a designer to generate structures in an interactive manner. While graph-theory-based tools and symbolic notation have contributed to the achievement of this objective, many recent programs have not managed to preserve an interface that keeps the designer active in the design process (Mruthyunjaya 2003). The PSEO concept serves to bridge the gap between automation and interaction. However, there is much remaining programming-intensive work to finish for this concept to come to fruition.

Since the program combines the use of two types of algorithms and is tasked with maintaining a responsive user interface, it presents a challenging programming-related undertaking. The program will also need to handle instances of errors efficiently, as error-checking within such a multi-layered program structure will be difficult for the user. Additionally, during the programming phase of implementation, it will be important to include a visual cataloguing function in the code to enable the creation of an atlas for the user, if such an atlas is required.

Areas for future work beyond the implementation of the current PSEO concept include a built-in atlas browser with catalogues of existing mechanisms that are searchable by the designer. If the mechanism atlases were grouped by function, path, motion and dwell (or hesitation) characteristics, the user could conduct a key word search and inspect possible candidate mechanisms. At this time, the most obvious obstacle to integrating an atlas is the challenge of cataloguing mechanisms in a nomenclature that can be translated into a visual format. There are not currently any applicable algorithms with the capability to automatically sketch abstract and functional diagrams of linkages. (Mruthyunjaya 2003)

Future work with regard to the PSEO program could include integrating a human constraint modeller to assist designers in finding appropriate linkages for human use. Additionally, in later stages of program development, a GCP could be designed specifically for the purpose of sketching kinematic models. Creating a simplified software interface that is independent from existing 3D solid modelling programs has the potential to speed up the run time of the program and make a more cohesive software package.

The final, and possibly the most important, suggestion for the future development of PSEO is the integration of force analysis. Checking the alignment of forces throughout the range of motion is vital to discovering singularities or other force-related design problems. Since PSEO relies on 2D models of linkages, vector analysis could be a potential substitute for a 3D solid model force and motion simulation.

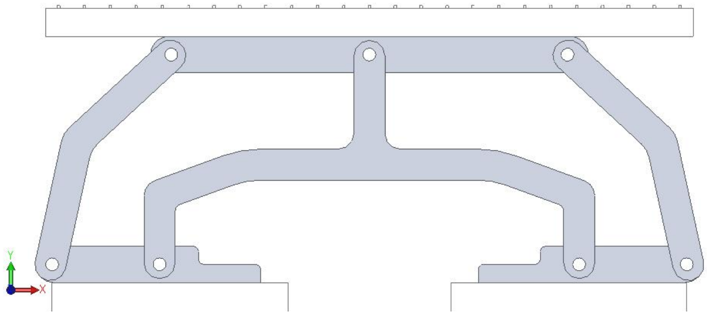
7.3 Discussion

The SMAC program and the related concept of design cataloguing has the immediate potential to benefit mechanism designers faced with challenging design tasks. It provides a systematic experimental synthesis approach that does not require the designer to program the linkage as sets of lines and constraints. It works from an existing 3D modelling package in a way that makes it easy for the designer to alter or completely change the topology of the mechanism being tested.

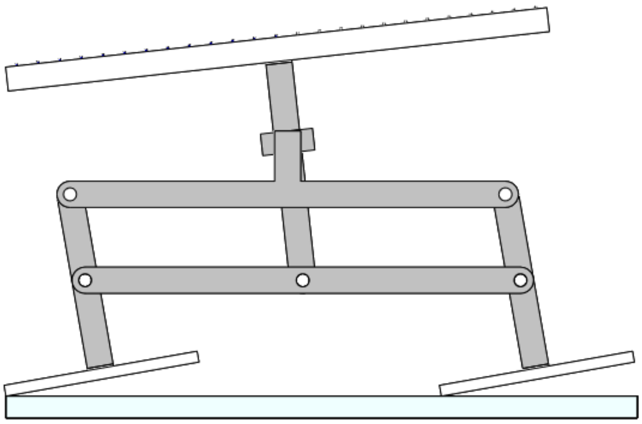
Once fully operational, the PSEO program has the potential to assist a future researcher in finding a fully suitable solution for the Skiboard. It serves the dual purpose of being a synthesis- and an optimisation-capable tool and can cover the entire design space in the search for solutions.

As the work with the Skiboard task has proven, interactive design tools are invaluable to a mechanism designer faced with a complex task. These kinds of tools are especially useful at the “fuzzy” front end of design, when topology has yet to be decided and dimensional combinations must be explored. For these tasks experimental methods often prove useful, as evidenced by the fact that many designers create ad hoc computer tools to assist with virtual experimentation. The major contribution of this thesis is to highlight the benefits of using experimentation in combination with other available tools and algorithms.

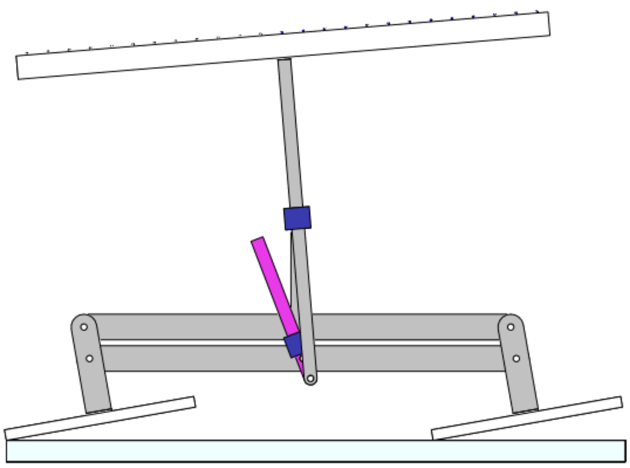
Appendix A



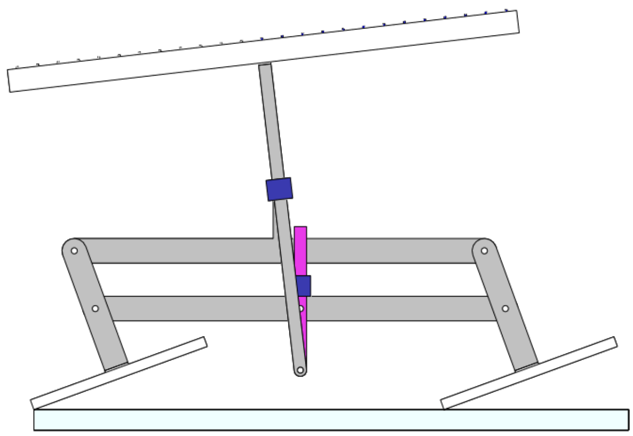
Concept 0



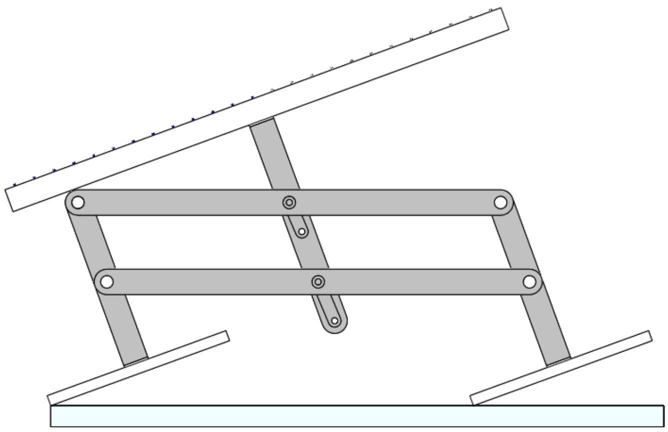
Concept 2



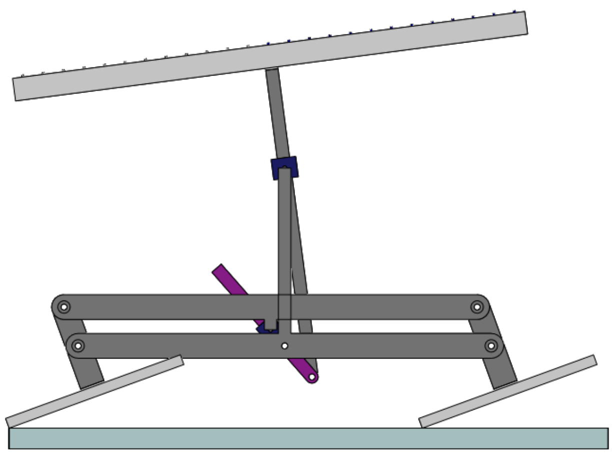
Concept 3



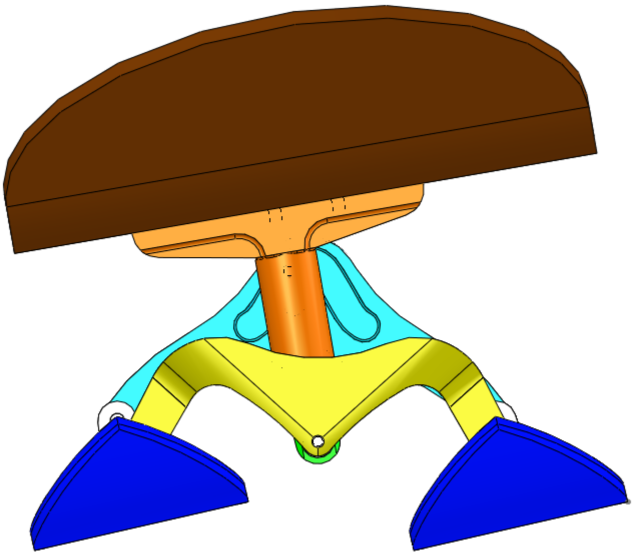
Concept 4



Concept 5



Concept 6



Concept 8

Appendix B

The images contained in this appendix correspond to the results of one iteration of experimental synthesis for the Concept 3 mechanism. Similar experiments using the same setup were also carried out for Concepts 4 thru 8. Refer to Chapter 3 for a detailed explanation.

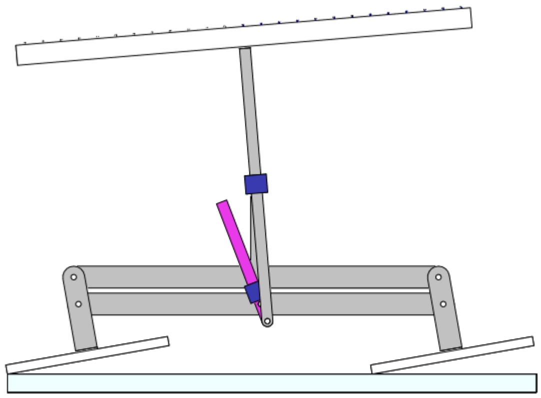
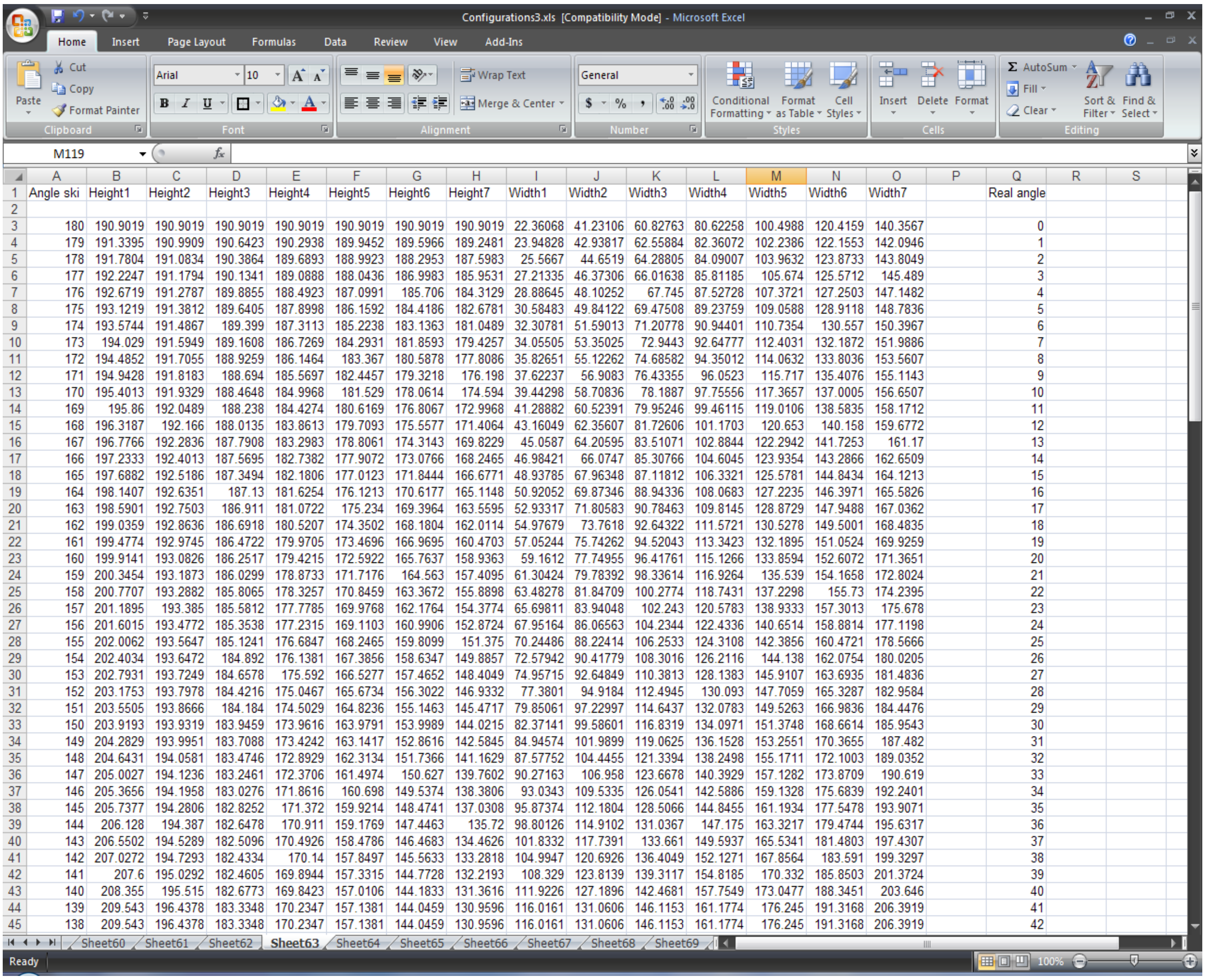
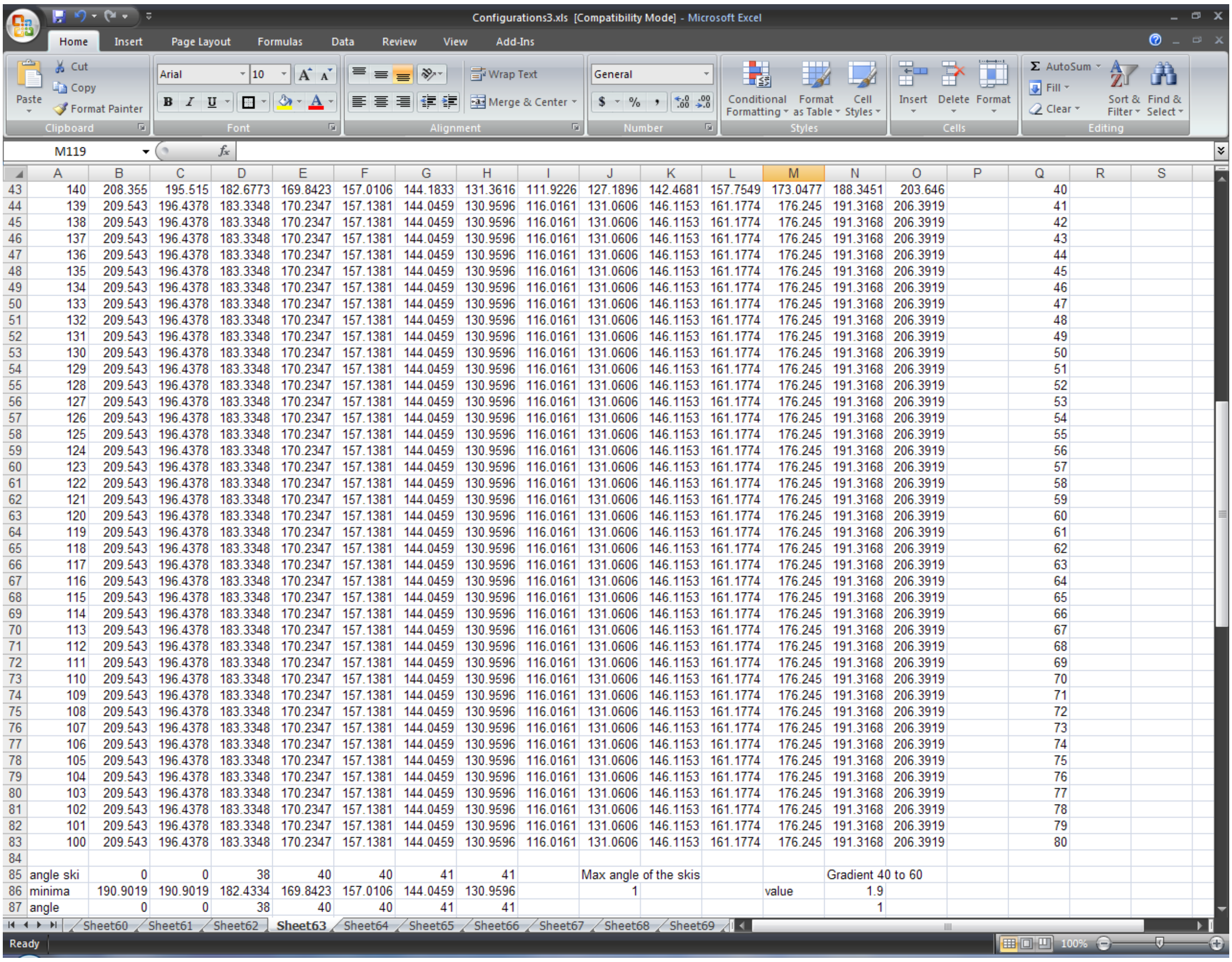


Figure 64: Concept 3 Mechanism



Angle ski	Height1	Height2	Height3	Height4	Height5	Height6	Height7	Width1	Width2	Width3	Width4	Width5	Width6	Width7	Real angle
180	190.9019	190.9019	190.9019	190.9019	190.9019	190.9019	190.9019	22.36068	41.23106	60.82763	80.62258	100.4988	120.4159	140.3567	0
179	191.3395	190.9909	190.6423	190.2938	189.9452	189.5966	189.2481	23.94828	42.93817	62.55884	82.36072	102.2386	122.1553	142.0946	1
178	191.7804	191.0834	190.3864	189.6893	188.9923	188.2953	187.5983	25.5667	44.6519	64.28805	84.09007	103.9632	123.8733	143.8049	2
177	192.2247	191.1794	190.1341	189.0888	188.0436	186.9983	185.9531	27.21335	46.37306	66.01638	85.81185	105.674	125.5712	145.489	3
176	192.6719	191.2787	189.8855	188.4923	187.0991	185.706	184.3129	28.88645	48.10252	67.745	87.52728	107.3721	127.2503	147.1482	4
175	193.1219	191.3812	189.6405	187.8998	186.1592	184.4186	182.6781	30.58483	49.84122	69.47508	89.23759	109.0588	128.9118	148.7836	5
174	193.5744	191.4867	189.399	187.3113	185.2238	183.1363	181.0489	32.30781	51.59013	71.20778	90.94401	110.7354	130.557	150.3967	6
173	194.029	191.5949	189.1608	186.7269	184.2931	181.8593	179.4257	34.05505	53.35025	72.9443	92.64777	112.4031	132.1872	151.9886	7
172	194.4852	191.7055	188.9259	186.1464	183.367	180.5878	177.8086	35.82651	55.12262	74.68582	94.35012	114.0632	133.8036	153.5607	8
171	194.9428	191.8183	188.694	185.5697	182.4457	179.3218	176.198	37.62237	56.9083	76.43355	96.0523	115.717	135.4076	155.1143	9
170	195.4013	191.9329	188.4648	184.9968	181.529	178.0614	174.594	39.44298	58.70836	78.1887	97.75556	117.3657	137.0005	156.6507	10
169	195.86	192.0489	188.238	184.4274	180.6169	176.8067	172.9968	41.28882	60.52391	79.95246	99.46115	119.0106	138.5835	158.1712	11
168	196.3187	192.166	188.0135	183.8613	179.7093	175.5577	171.4064	43.16049	62.35607	81.72606	101.1703	120.653	140.158	159.6772	12
167	196.7766	192.2836	187.7908	183.2983	178.8061	174.3143	169.8229	45.0587	64.20595	83.51071	102.8844	122.2942	141.7253	161.17	13
166	197.2333	192.4013	187.5695	182.7382	177.9072	173.0766	168.2465	46.98421	66.0747	85.30766	104.6045	123.9354	143.2866	162.6509	14
165	197.6882	192.5186	187.3494	182.1806	177.0123	171.8444	166.6771	48.93785	67.96348	87.11812	106.3321	125.5781	144.8434	164.1213	15
164	198.1407	192.6351	187.13	181.6254	176.1213	170.6177	165.1148	50.92052	69.87346	88.94336	108.0683	127.2235	146.3971	165.5826	16
163	198.5901	192.7503	186.911	181.0722	175.234	169.3964	163.5595	52.93317	71.80583	90.78463	109.8145	128.8729	147.9488	167.0362	17
162	199.0359	192.8636	186.6918	180.5207	174.3502	168.1804	162.0114	54.97679	73.7618	92.64322	111.5721	130.5278	149.5001	168.4835	18
161	199.4774	192.9745	186.4722	179.9705	173.4696	166.9695	160.4703	57.05244	75.74262	94.52043	113.3423	132.1895	151.0524	169.9259	19
160	199.9141	193.0826	186.2517	179.4215	172.5922	165.7637	158.9363	59.1612	77.74955	96.41761	115.1266	133.8594	152.6072	171.3651	20
159	200.3454	193.1873	186.0299	178.8733	171.7176	164.563	157.4095	61.30424	79.78392	98.33614	116.9264	135.539	154.1658	172.8024	21
158	200.7707	193.2882	185.8065	178.3257	170.8459	163.3672	155.8898	63.48278	81.84709	100.2774	118.7431	137.2298	155.73	174.2395	22
157	201.1895	193.385	185.5812	177.7785	169.9768	162.1764	154.3774	65.69811	83.94048	102.243	120.5783	138.9333	157.3013	175.678	23
156	201.6015	193.4772	185.3538	177.2315	169.1103	160.9906	152.8724	67.95164	86.06563	104.2344	122.4336	140.6514	158.8814	177.1198	24
155	202.0062	193.5647	185.1241	176.6847	168.2465	159.8099	151.375	70.24486	88.22414	106.2533	124.3108	142.3856	160.4721	178.5666	25
154	202.4034	193.6472	184.892	176.1381	167.3856	158.6347	149.8857	72.57942	90.41779	108.3016	126.2116	144.138	162.0754	180.0205	26
153	202.7931	193.7249	184.6578	175.592	166.5277	157.4652	148.4049	74.95715	92.64849	110.3813	128.1383	145.9107	163.6935	181.4836	27
152	203.1753	193.7978	184.4216	175.0467	165.6734	156.3022	146.9332	77.3801	94.9184	112.4945	130.093	147.7059	165.3287	182.9584	28
151	203.5505	193.8666	184.184	174.5029	164.8236	155.1463	145.4717	79.85061	97.22997	114.6437	132.0783	149.5263	166.9836	184.4476	29
150	203.9193	193.9319	183.9459	173.9616	163.9791	153.9989	144.0215	82.37141	99.58601	116.8319	134.0971	151.3748	168.6614	185.9543	30
149	204.2829	193.9951	183.7088	173.4242	163.1417	152.8616	142.5845	84.94574	101.9899	119.0625	136.1528	153.2551	170.3655	187.482	31
148	204.6431	194.0581	183.4746	172.8929	162.3134	151.7366	141.1629	87.57752	104.4455	121.3394	138.2498	155.1711	172.1003	189.0352	32
147	205.0027	194.1236	183.2461	172.3706	161.4974	150.627	139.7602	90.27163	106.958	123.6678	140.3929	157.1282	173.8709	190.619	33
146	205.3656	194.1958	183.0276	171.8616	160.698	149.5374	138.3806	93.0343	109.5335	126.0541	142.5886	159.1328	175.6839	192.2401	34
145	205.7377	194.2806	182.8252	171.372	159.9214	148.4741	137.0308	95.87374	112.1804	128.5066	144.8455	161.1934	177.5478	193.9071	35
144	206.128	194.387	182.6478	170.911	159.1769	147.4463	135.72	98.80126	114.9102	131.0367	147.175	163.3217	179.4744	195.6317	36
143	206.5502	194.5289	182.5096	170.4926	158.4786	146.4683	134.4626	101.8332	117.7391	133.661	149.5937	165.5341	181.4803	197.4307	37
142	207.0272	194.7293	182.4334	170.14	157.8497	145.5633	133.2818	104.9947	120.6926	136.4049	152.1271	167.8564	183.591	199.3297	38
141	207.6	195.0292	182.4605	169.8944	157.3315	144.7728	132.2193	108.329	123.8139	139.3117	154.8185	170.332	185.8503	201.3724	39
140	208.355	195.515	182.6773	169.8423	157.0106	144.1833	131.3616	111.9226	127.1896	142.4681	157.7549	173.0477	188.3451	203.646	40
139	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919	41
138	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919	42

Figure 65: Concept 3 Excel Data Screenshot – Dimensional Configuration 63 (Top of Table)



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
43	140	208.355	195.515	182.6773	169.8423	157.0106	144.1833	131.3616	111.9226	127.1896	142.4681	157.7549	173.0477	188.3451	203.646		40
44	139	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		41
45	138	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		42
46	137	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		43
47	136	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		44
48	135	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		45
49	134	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		46
50	133	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		47
51	132	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		48
52	131	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		49
53	130	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		50
54	129	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		51
55	128	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		52
56	127	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		53
57	126	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		54
58	125	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		55
59	124	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		56
60	123	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		57
61	122	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		58
62	121	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		59
63	120	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		60
64	119	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		61
65	118	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		62
66	117	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		63
67	116	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		64
68	115	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		65
69	114	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		66
70	113	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		67
71	112	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		68
72	111	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		69
73	110	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		70
74	109	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		71
75	108	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		72
76	107	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		73
77	106	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		74
78	105	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		75
79	104	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		76
80	103	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		77
81	102	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		78
82	101	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		79
83	100	209.543	196.4378	183.3348	170.2347	157.1381	144.0459	130.9596	116.0161	131.0606	146.1153	161.1774	176.245	191.3168	206.3919		80
84																	
85	angle ski	0	0	38	40	40	41	41		Max angle of the skis				Gradient 40 to 60			
86	minima	190.9019	190.9019	182.4334	169.8423	157.0106	144.0459	130.9596		1			value	1.9			
87	angle	0	0	38	40	40	41	41						1			

Figure 66: Concept 3 Excel Data Screenshot – Dimensional Configuration 63 (Bottom of Table)

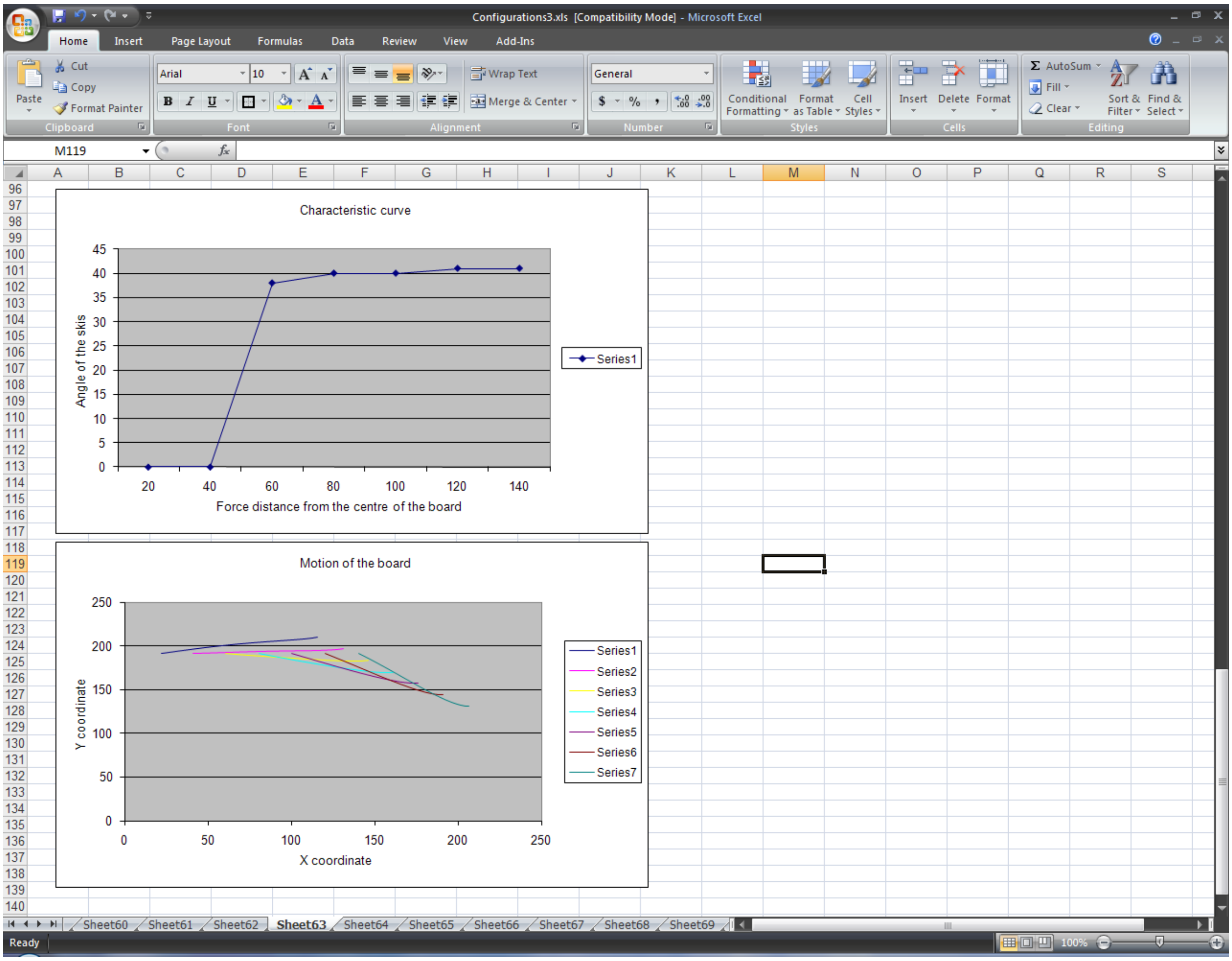


Figure 67: Screenshot - Result Plots in Excel

Appendix C

```
'SMAC Code for Configuration Creation

Dim swApp As Object
Dim Part As Object
Dim SelMgr As Object
Dim boolstatus As Boolean
Dim longstatus As Long, longwarnings As Long
Dim Feature As Object
Sub mechanismtest()


Set xlBook = GetObject("C:\Temp\Configurations6.XLSM") 'xlsm file
format indicates Excel 2007 file with embedded macros
xlBook.Application.Visible = True
xlBook.Parent.Windows(1).Visible = True
Set Configurations = xlBook.Worksheets(1)

Set xlBook2 = GetObject("C:\Temp\Concept6.XLS")
xlBook2.Application.Visible = True
xlBook2.Parent.Windows(2).Visible = True
Set DimSheet = xlBook2.Worksheets(5)


Pi = 3.141592

For I = 3 To 10 'I is the row on sheet "Configurations"

    Component1 = (Configurations.Range("A" & I).Value) / 1000 'small
cuff
    Component2 = (Configurations.Range("B" & I).Value) / 1000 'leg
height
    Component3 = (Configurations.Range("C" & I).Value) / 1000 'top
slider
    Component4 = (Configurations.Range("D" & I).Value) / 1000 'radius
    Component5 = (Configurations.Range("E" & I).Value) / 1000
'vertical link

    Set swApp = Application.SldWorks

    Set Part = swApp.ActiveDoc
    Set SelMgr = Part.SelectionManager

        boolstatus = Part.Extension.SelectByID2("D1@Extrude5@top
link6-1@Assem6.SLDASM", "DIMENSION", 0, 0, 0, False, 0, Nothing, 0)
        Part.Parameter("D1@Extrude5@top link6-1.Part").SystemValue =
Component1
        Part.ClearSelection2 True
        Part.InsertSketch2 True
        boolstatus = Part.EditRebuild3
```

```
            boolstatus = Part.Extension.SelectByID2("D1@Sketch1@side
link6-1@Assem6", "DIMENSION", 0, 0, 0, False, 0, Nothing, 0)
            Part.Parameter("D1@Sketch1@side link6-
1.Part").SystemValue = Component2
            Part.ClearSelection2 True
            Part.InsertSketch2 True
            boolstatus = Part.EditRebuild3

                boolstatus =
Part.Extension.SelectByID2("D1@Extrude2@bottom link6-1@Assem6",
"DIMENSION", 0, 0, 0, False, 0, Nothing, 0)
                Part.Parameter("D1@Extrude2@bottom link6-
1.Part").SystemValue = Component3
                Part.ClearSelection2 True
                Part.InsertSketch2 True
                boolstatus = Part.EditRebuild3

                    boolstatus =
Part.Extension.SelectByID2("D6@Sketch1@radius6-1@Assem6",
"DIMENSION", 0, 0, 0, False, 0, Nothing, 0)
                    Part.Parameter("D6@Sketch1@radius6-
1.Part").SystemValue = Component4
                    Part.ClearSelection2 True
                    Part.InsertSketch2 True
                    boolstatus = Part.EditRebuild3

                        boolstatus =
Part.Extension.SelectByID2("D1@Sketch1@vertical link6-1@Assem6",
"DIMENSION", 0, 0, 0, False, 0, Nothing, 0)
                        Part.Parameter("D1@Sketch1@vertical link6-
1.Part").SystemValue = Component5
                        Part.ClearSelection2 True
                        Part.InsertSketch2 True
                        boolstatus = Part.EditRebuild3

        DimSheet.Range("C3").Value = Component3 * 1000   'sets link
dimension in XL component model
        DimSheet.Range("C4").Value = Component5 * 1000
        DimSheet.Range("C7").Value = Component2 * 1000
        'DimSheet.Range("C8").Value
        DimSheet.Range("C9").Value = Component4 * 1000
        DimSheet.Range("C10").Value = Component1 * 1000


                Set xlSheet = xlBook.Worksheets(I - 1)

                For J = 3 To 63 Step 1  'J is the row on sheet
"xlSheet"

                    Angle = (xlSheet.Range("A" & J).Value)

                    boolstatus =
Part.Extension.SelectByID2("D1@SkiAngle@Assem3.SLDASM", "DIMENSION",
0, 0, 0, False, 0, Nothing, 0)

Part.Parameter("D1@SkiAngle@Annotations").SystemValue = Pi - Angle
```

```
                        Part.ClearSelection2 True
                        boolstatus = Part.EditRebuild3


                    xlSheet.Range("C" & J).Value =
Part.Parameter("RD1@Annotations").SystemValue * 1000 'Width20
                    xlSheet.Range("D" & J).Value =
Part.Parameter("RD2@Annotations").SystemValue * 1000  'Width40
                    xlSheet.Range("E" & J).Value =
Part.Parameter("RD3@Annotations").SystemValue * 1000  'Width60
                    xlSheet.Range("F" & J).Value =
Part.Parameter("RD4@Annotations").SystemValue * 1000  'Width80
                    xlSheet.Range("G" & J).Value =
Part.Parameter("RD5@Annotations").SystemValue * 1000  'Width100
                    xlSheet.Range("H" & J).Value =
Part.Parameter("RD6@Annotations").SystemValue * 1000  'Width120

                    xlSheet.Range("I" & J).Value =
Part.Parameter("RD7@Annotations").SystemValue * 1000  'Height20
                    xlSheet.Range("J" & J).Value =
Part.Parameter("RD8@Annotations").SystemValue * 1000  'Height40
                    xlSheet.Range("K" & J).Value =
Part.Parameter("RD9@Annotations").SystemValue * 1000  'Height60
                    xlSheet.Range("L" & J).Value =
Part.Parameter("RD10@Annotations").SystemValue * 1000  'Height80
                    xlSheet.Range("M" & J).Value =
Part.Parameter("RD11@Annotations").SystemValue * 1000  'Height100
                    xlSheet.Range("N" & J).Value =
Part.Parameter("RD12@Annotations").SystemValue * 1000  'Height120

                    Next J

                    Part.SaveAs2 "C:\Temp\DA Mechanism.JPG", 0, True,
False 'capture "screenshot" of mechanism

                    Set WrdApp = GetObject("c:\temp\test
results.doc") 'get Word document to record results
                        WrdApp.Application.Visible = True

                    'This Word document must be adjusted so that the
margins are 2 cm on top & bottom and 3 at the sides.

                    Set WrdSelection = WrdApp.ActiveWindow.Selection

                    With WrdSelection
                        .Font.Bold = True
                        .TypeText Text:="Configuration " & (I - 1)
'types the configuration # before the images
                        .TypeParagraph
                        .TypeParagraph
                    End With


                        Set MechPic =
WrdSelection.InlineShapes.AddPicture(FileName:="C:\Temp\da
mechanism.jpg", _
                        LinkToFile:=False, SaveWithDocument:=True)
```

```
                        With MechPic
                            .ScaleHeight = 28
                            .ScaleWidth = 28
                        End With

                    WrdSelection.TypeParagraph

                    xlBook.Sheets("CCurve" & (I - 1)).CopyPicture
'copy Characteristic Curve to paste into Word
                    WrdApp.ActiveWindow.Selection.Paste

                    xlBook.Sheets("Initiation" & (I - 1)).CopyPicture
                    WrdApp.ActiveWindow.Selection.Paste

                    WrdSelection.TypeParagraph

                    xlBook2.Sheets("Component Profiles
30").CopyPicture
                    WrdApp.ActiveWindow.Selection.Paste

                    xlBook2.Sheets("Component Profiles
120").CopyPicture
                    WrdApp.ActiveWindow.Selection.Paste


                    WrdSelection.TypeParagraph
                    WrdSelection.TypeParagraph
                    WrdSelection.TypeParagraph
                    WrdSelection.TypeParagraph
                    WrdSelection.TypeParagraph
                    WrdSelection.TypeParagraph

                    DimSheet.Range("A1:C9").Copy
                    WrdApp.ActiveWindow.Selection.Paste

                    WrdSelection.TypeParagraph


                    ResetSkiAngle = Pi - xlSheet.Range("A43").Value

                    boolstatus =
Part.Extension.SelectByID2("D1@SkiAngle@DA Mechanism.SLDASM",
"DIMENSION", 0, 0, 0, False, 0, Nothing, 0)
                        Part.Parameter("D1@SkiAngle").SystemValue =
ResetSkiAngle
                        boolstatus = Part.EditRebuild3

                        ResetSkiAngle = Pi -
xlSheet.Range("A33").Value

                    boolstatus =
Part.Extension.SelectByID2("D1@SkiAngle@DA Mechanism.SLDASM",
"DIMENSION", 0, 0, 0, False, 0, Nothing, 0)
                        Part.Parameter("D1@SkiAngle").SystemValue =
ResetSkiAngle
                        boolstatus = Part.EditRebuild3
```

```
                        ResetSkiAngle = Pi -
xlSheet.Range("A3").Value

                    boolstatus =
Part.Extension.SelectByID2("D1@SkiAngle@DA Mechanism.SLDASM",
"DIMENSION", 0, 0, 0, False, 0, Nothing, 0)
                        Part.Parameter("D1@SkiAngle").SystemValue =
ResetSkiAngle
                        boolstatus = Part.EditRebuild3

Next I

End Sub
```

Appendix D

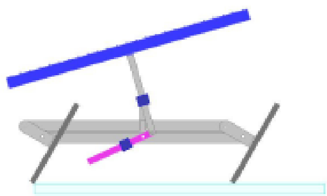
Component1	Component2	Component3	Component4	Component5	*Sheet No.*
s	l	g	r	v	
6	30	30	10	80	*2*
6	30	30	15	80	*3*
6	30	30	20	80	*4*
6	30	40	10	80	*5*
6	30	40	15	80	*6*
6	30	40	20	80	*7*
6	30	50	10	80	*8*
6	30	50	15	80	*9*
6	30	50	20	80	*10*
6	40	30	10	80	*11*
6	40	30	15	80	*12*
6	40	30	20	80	*13*
6	40	40	10	80	*14*
6	40	40	15	80	*15*
6	40	40	20	80	*16*
6	40	50	10	80	*17*
6	40	50	15	80	*18*
6	40	50	20	80	*19*
6	30	30	10	140	*20*
6	30	30	15	140	*21*
6	30	30	20	140	*22*
6	30	40	10	140	*23*
6	30	40	15	140	*24*
6	30	40	20	140	*25*
6	30	50	10	140	*26*
6	30	50	15	140	*27*
6	30	50	20	140	*28*
6	40	30	10	140	*29*
6	40	30	15	140	*30*
6	40	30	20	140	*31*
6	40	40	10	140	*32*
6	40	40	15	140	*33*
6	40	40	20	140	*34*
6	40	50	10	140	*35*
6	40	50	15	140	*36*
6	40	50	20	140	*37*
12	30	30	10	80	*38*
12	30	30	15	80	*39*
12	30	30	20	80	*40*
12	30	40	20	80	*41*
12	30	40	15	80	*42*
12	30	40	10	80	*43*
12	30	50	10	80	*44*
12	30	50	15	80	*45*
12	30	50	20	80	*46*
12	40	30	20	80	*47*
12	40	30	15	80	*48*
12	40	30	10	80	*49*
12	40	40	10	80	*50*

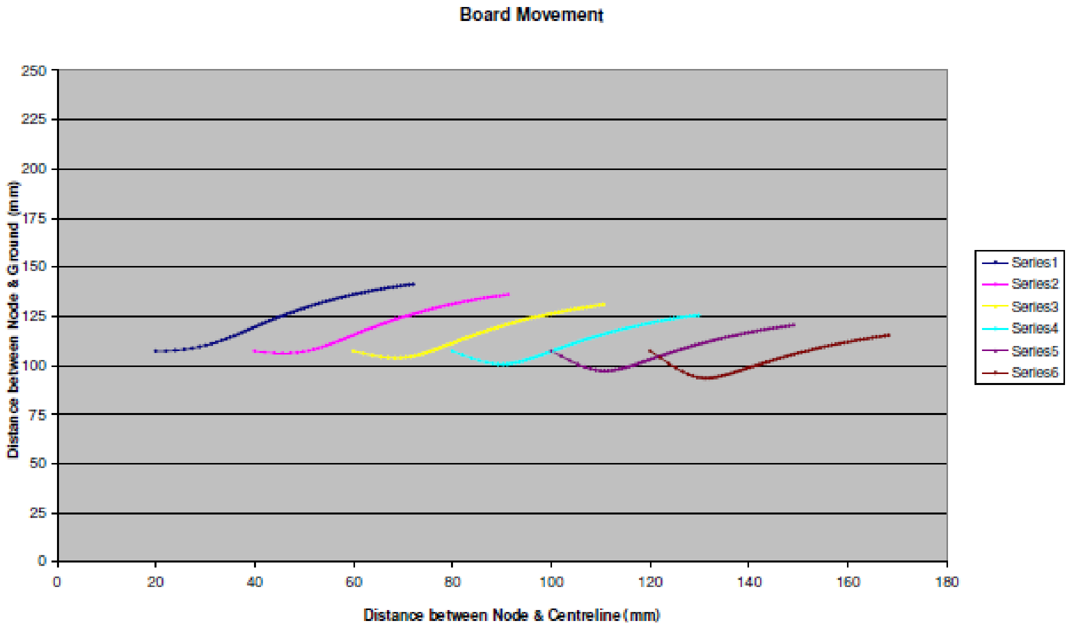
r 10, 15, 20,
g 30, 40, 50
l 30, 40
s 6, 12
v 80, 140
ski sep: 20mm

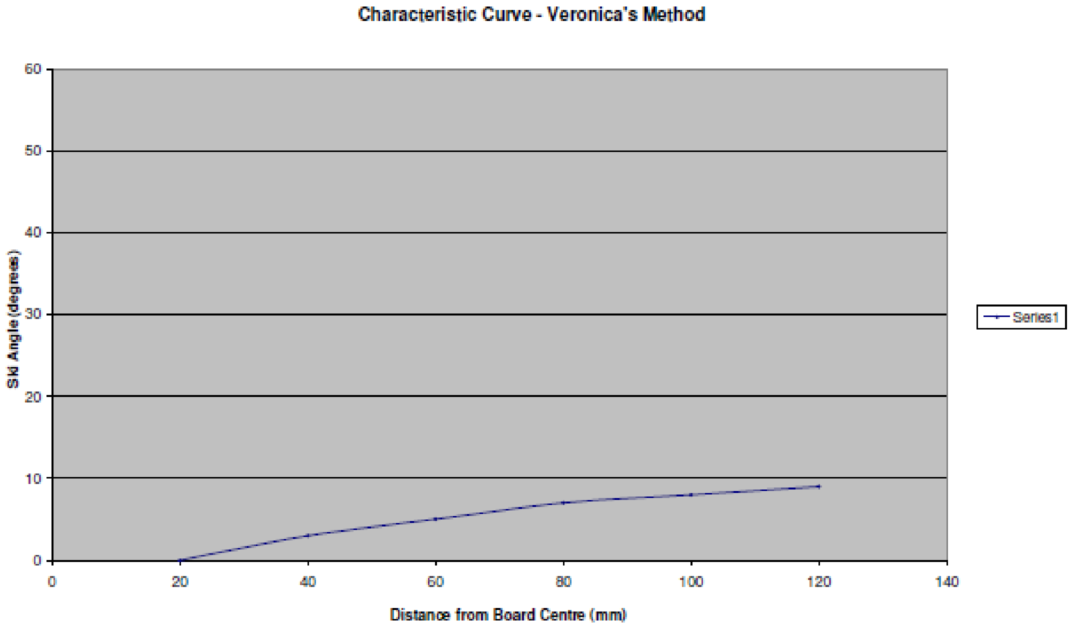
r radius
g top slider
l leg height
s bottom slider
v vertical link

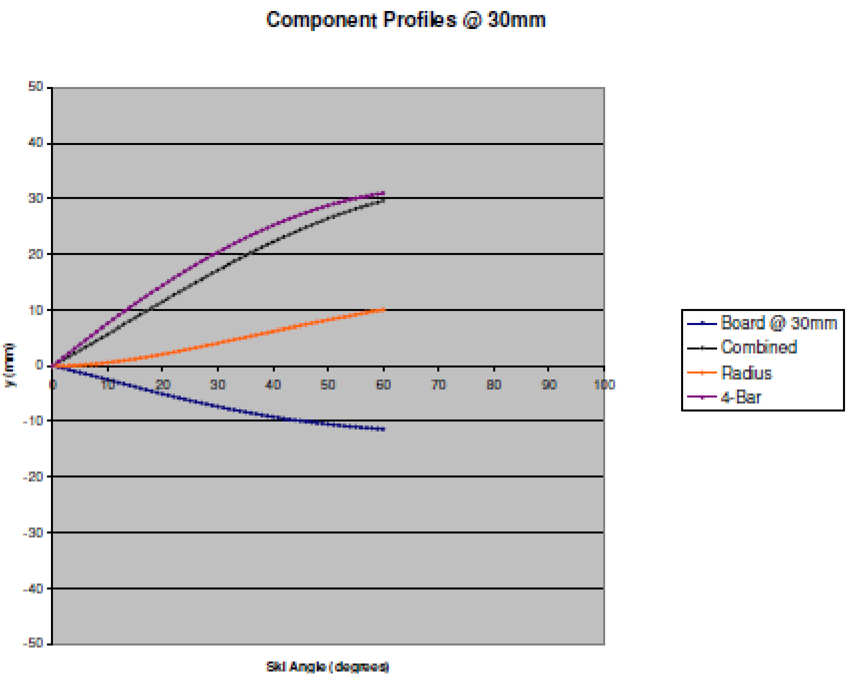
12	40	40	15	80	*51*
12	40	40	20	80	*52*
12	40	50	20	80	*53*
12	40	50	15	80	*54*
12	40	50	10	80	*55*
12	30	30	10	140	*56*
12	30	30	15	140	*57*
12	30	30	20	140	*58*
12	30	40	20	140	*59*
12	30	40	15	140	*60*
12	30	40	10	140	*61*
12	30	50	10	140	*62*
12	30	50	15	140	*63*
12	30	50	20	140	*64*
12	40	30	20	140	*65*
12	40	30	15	140	*66*
12	40	30	10	140	*67*
12	40	40	10	140	*68*
12	40	40	15	140	*69*
12	40	40	20	140	*70*
12	40	50	20	140	*71*
12	40	50	15	140	*72*
12	40	50	10	140	*73*

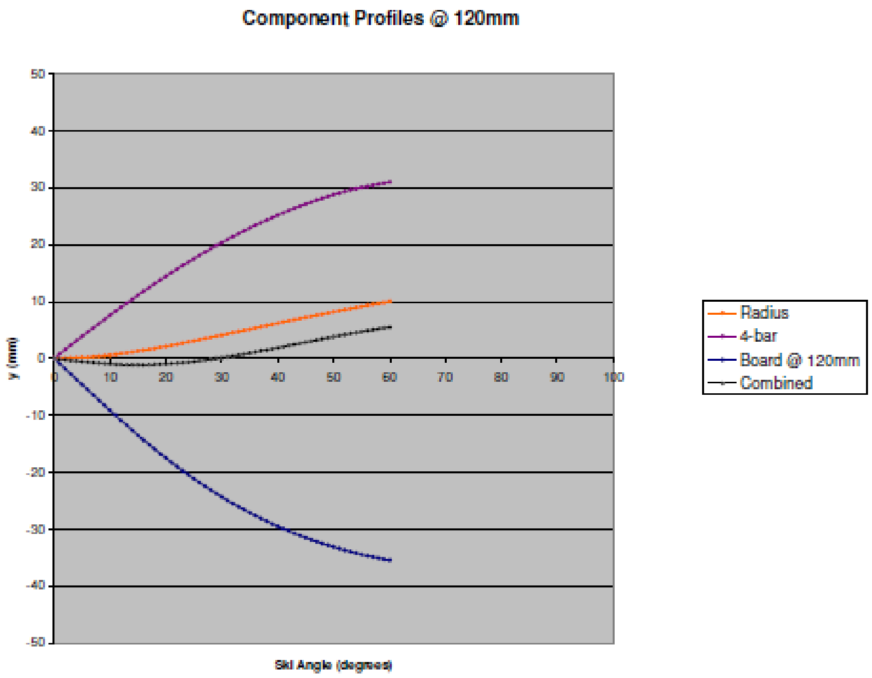
Configuration 38







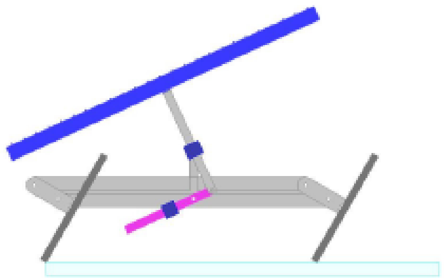


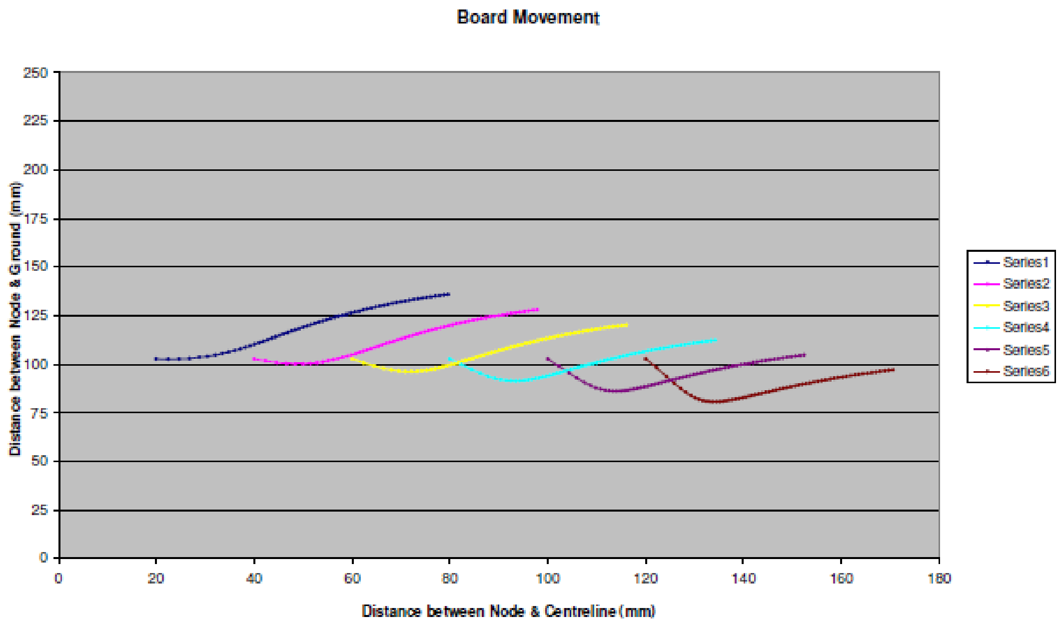


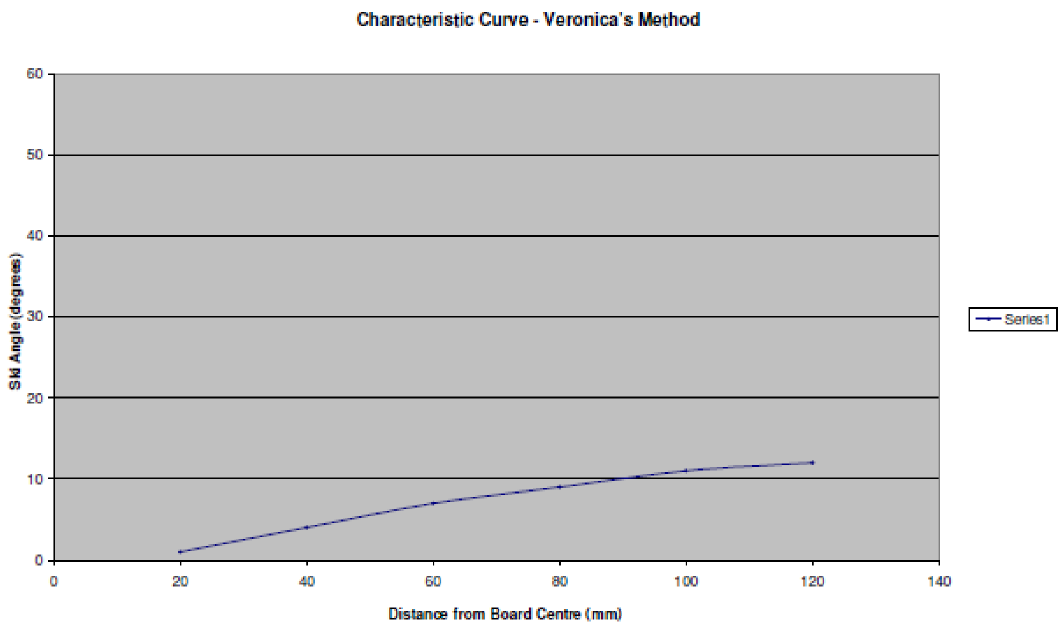
Skiboard Dimensions

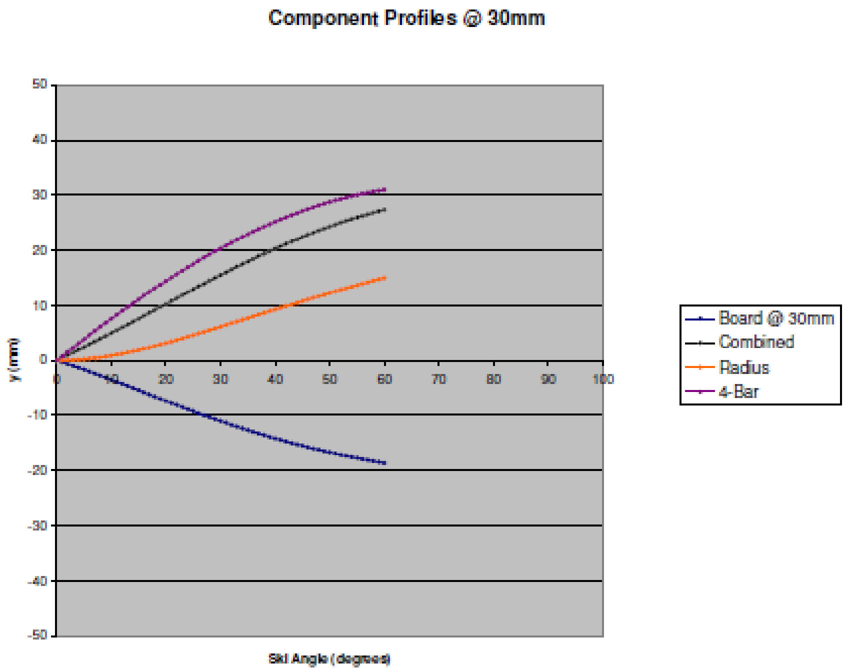
d	36
v	92
h	200
w	90
t	16
l	36
r	10
n	18

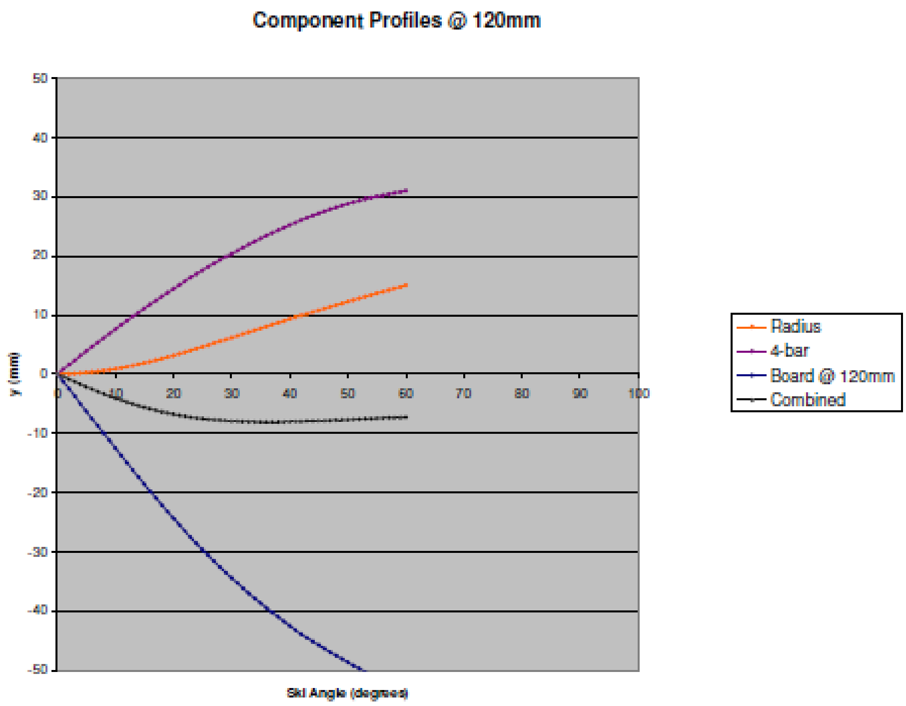
Configuration 39







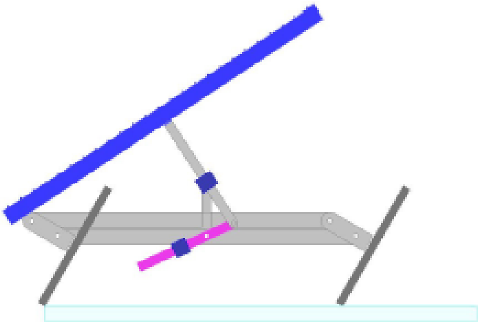


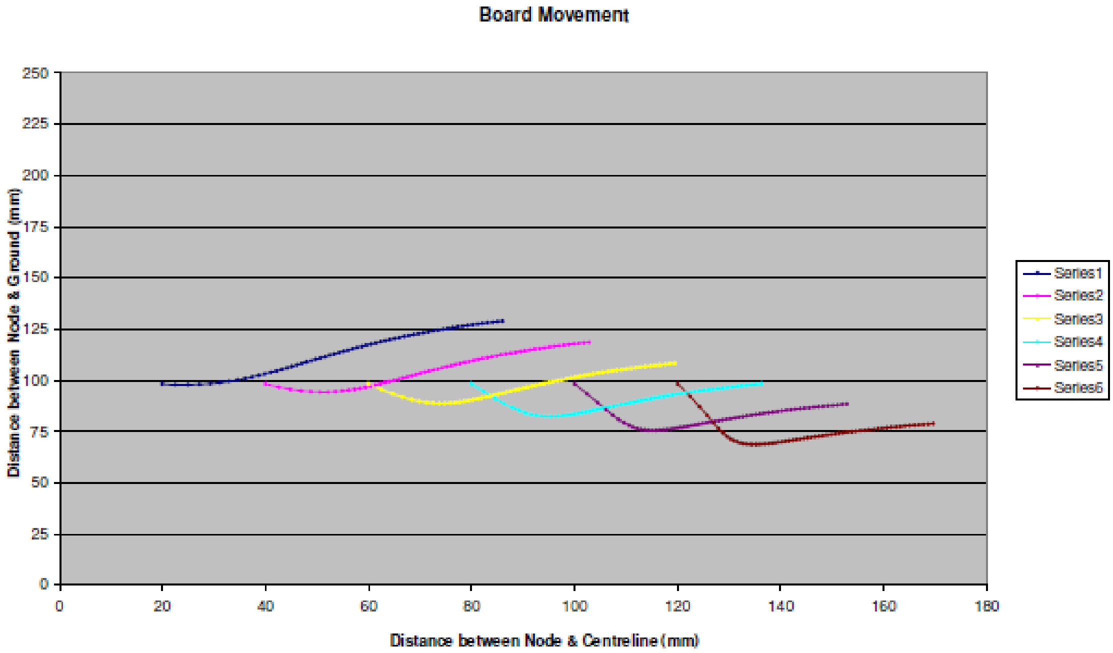


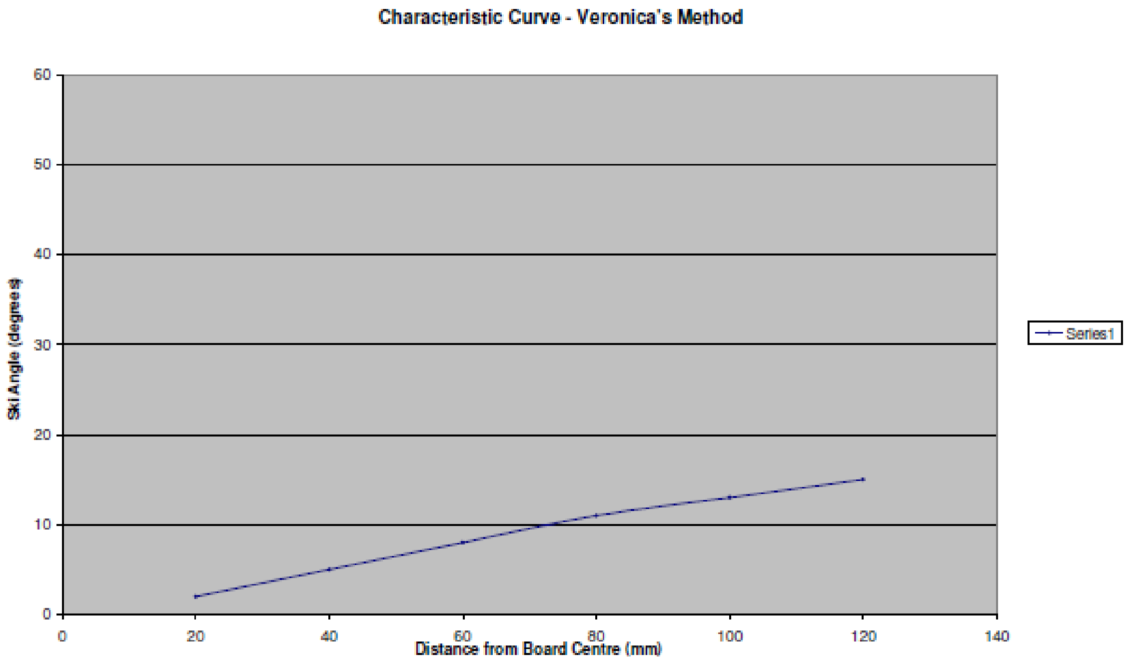
Skiboard Dimensions

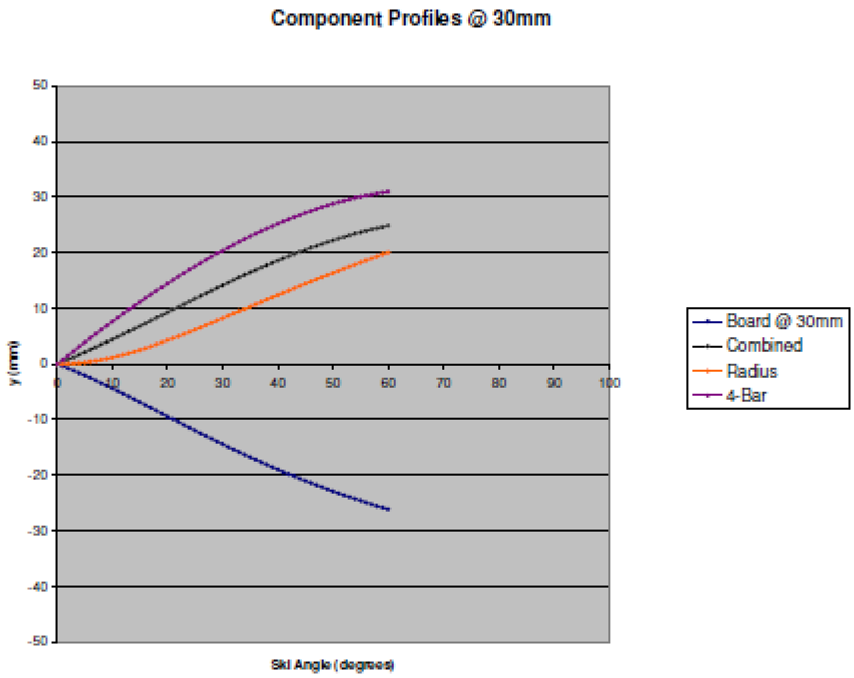
d	36
v	92
h	200
w	90
t	16
l	36
r	15
n	18

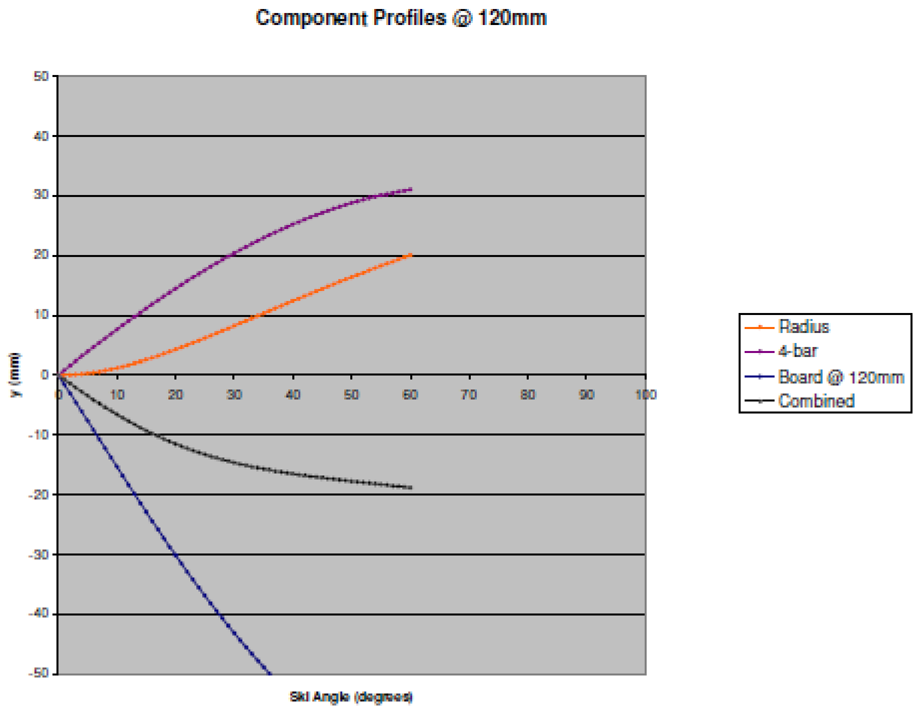
Configuration 40











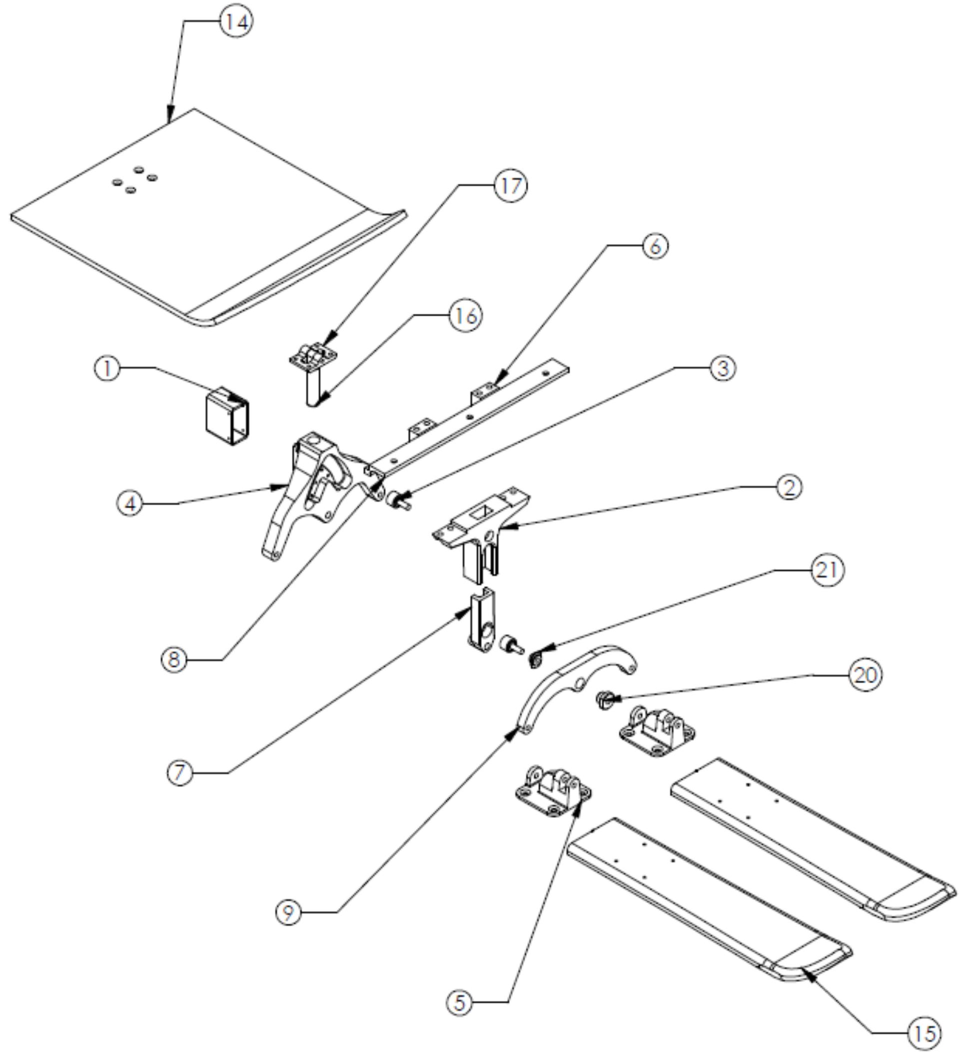
Skiboard Dimensions

d	36
v	92
h	200
w	90
t	16
l	36
r	20
n	18

Appendix E

DO NOT SCALE

BREAK ALL SHARP EDGES



ITEM NO.	PART NUMBER	MAT'L / DESCRIPTION	QTY.	DWG. #
1	Bridge	Aluminium	1	2
2	Compressor	6XXX Grade Al	2	3
3	Cam follower	free issue part	4	
4	Lower cross link	6XXX Grade Al	2	4
5	Ski mount	6XXX Grade Al	4	5
6	Housing bearing square	free issue part	4	
7	Inverted pendulum	Stainless Steel	2	6
8	Transverse slide rail	free issue part	2	
9	Upper cross link	6XXX Grade Al	2	7
10	6X20 shoulder	standard part not shown	4	
11	B18.2.3.5M - Hex bolt M5 x 0.8 x 25 --16N	standard part not shown	1	
12	B18.6.7M - M6 x 1.0 x 8 Type I Cross Recessed FHMS --8N	standard part not shown	16	
13	4mm Dome Head Screw	standard part not shown	8	
14	RealDeck	free issue part	1	
15	RealSkis	free issue part	2	
16	Tilting slide	Stainless Steel	2	8
17	Tilting head	Aluminium	2	9
18	6X45 shoulder	standard part not shown	4	
19	8X35 shoulder	standard part not shown	2	
20	Lower cam nut	Stainless Steel	2	10
21	Lower cam connector	Stainless Steel	2	11
22	Cam Insert	not shown in assembly	2	12

NOTE:
Half of mechanism shown for clarity.

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SHEET No. 1 of 1

Skiboard Assembly

ALL DIMENSIONS IN mm

SCALE : 2:1 -- (A3) ALL DIMENSIONS IN mm

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MECHANICAL ENGINEERING DEPT. CH.CH. N.Z.

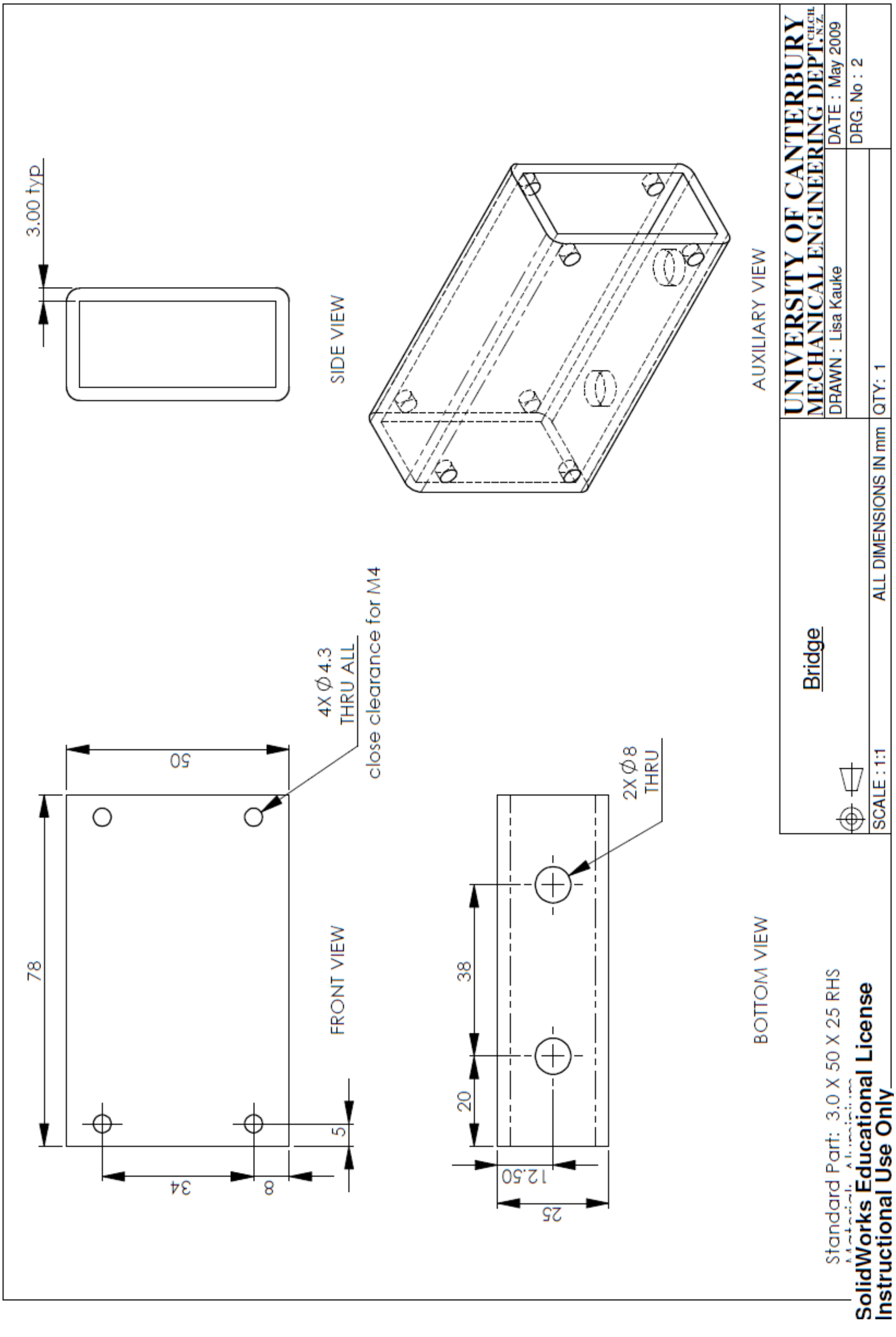
DRAWN : Lisa Kauke

DATE : July 2009

CHECKED :

APPROVED :

DRG. No : 1


3.00 typ
SIDE VIEW
AUXILIARY VIEW
50
78
4X Ø4.3
THRU ALL
close clearance for M4
FRONT VIEW
5
34
8
2X Ø8
THRU
38
20
12.50
25
BOTTOM VIEW
Standard Part: 3.0 X 50 X 25 RHS
UNIVERSITY OF CANTERBURY
MECHANICAL ENGINEERING DEPT. CH.CH. N.Z.
DRAWN : Lisa Kauke
DATE : May 2009
DRG. No : 2
Bridge
SCALE : 1:1
ALL DIMENSIONS IN mm
QTY: 1
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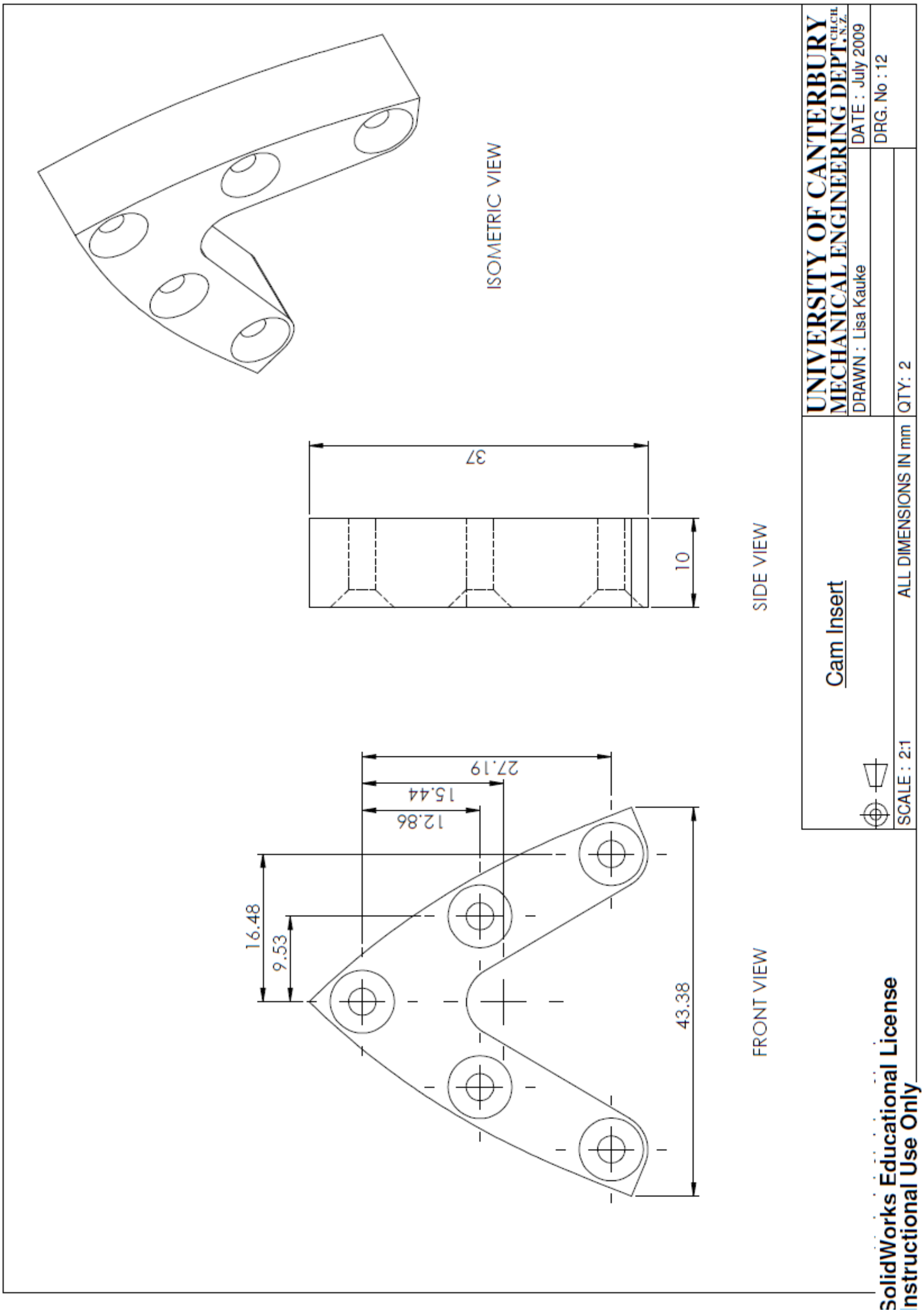
ISOMETRIC VIEW
37
10
SIDE VIEW
27.19
15.44
12.86
16.48
9.53
43.38
FRONT VIEW
UNIVERSITY OF CANTERBURY
MECHANICAL ENGINEERING DEPT. CH.CH. N.Z.
DRAWN : Lisa Kauke
DATE : July 2009
DRG. No : 12
Cam Insert
SCALE : 2:1
ALL DIMENSIONS IN mm
QTY: 2
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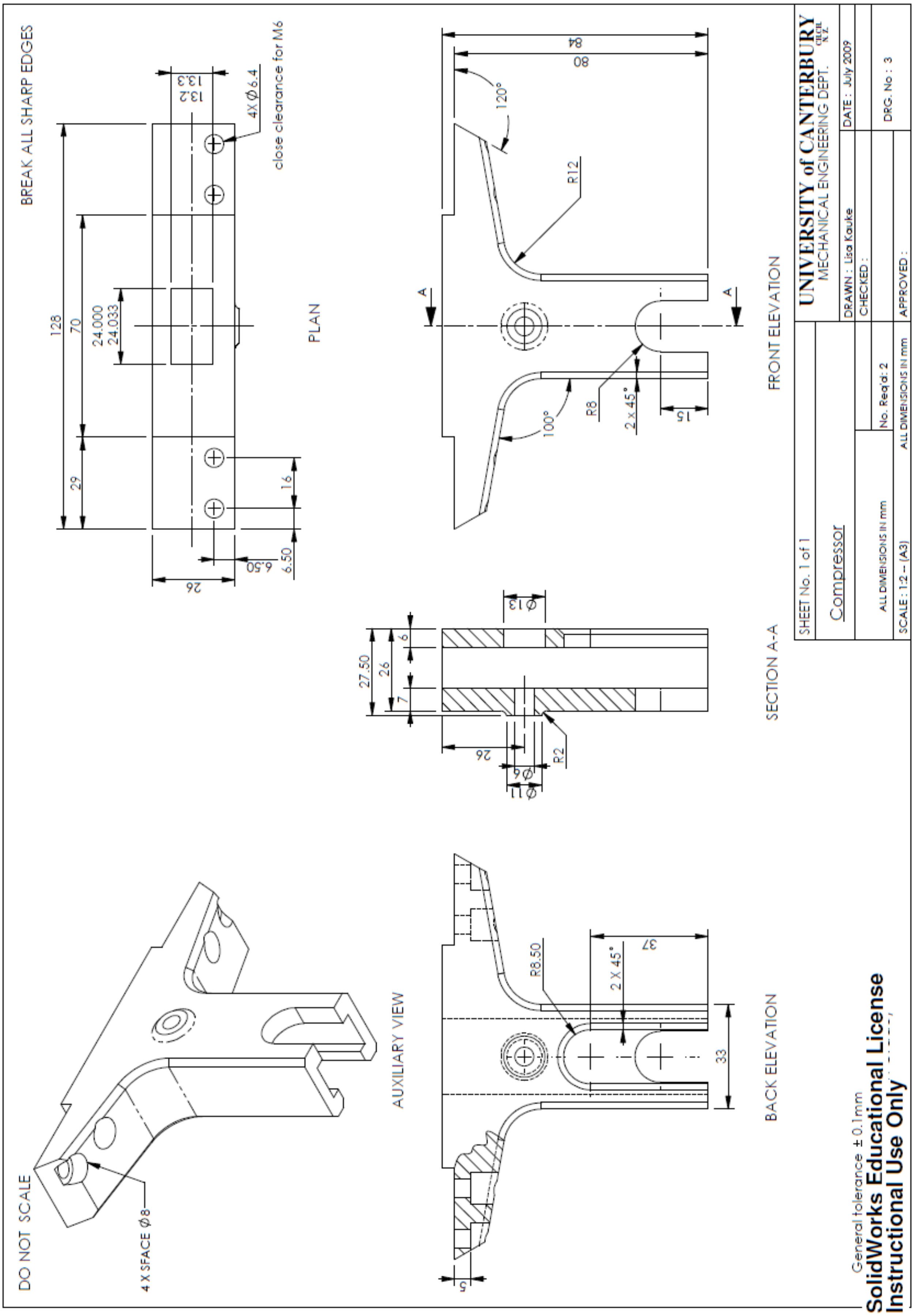
BREAK ALL SHARP EDGES
DO NOT SCALE
4X Ø6.4
close clearance for M6
PLAN
FRONT ELEVATION
SECTION A-A
AUXILIARY VIEW
BACK ELEVATION
4 X SFACE Ø8
R12
R8
R2
R8.50
2 x 45°
120°
100°
128
70
29
24.000
24.033
13.3
13.2
16
6.50
26
84
80
15
Ø13
27.50
6
7
Ø6
Ø11
37
33
5
SHEET No. 1 of 1
Compressor
ALL DIMENSIONS IN mm
SCALE : 1:2 -- (A3)
No. Req'd : 2
UNIVERSITY of CANTERBURY
MECHANICAL ENGINEERING DEPT.
DRAWN : Lisa Kauke
CHECKED :
APPROVED :
DATE : July 2009
DRG. No : 3
General tolerance ± 0.1mm
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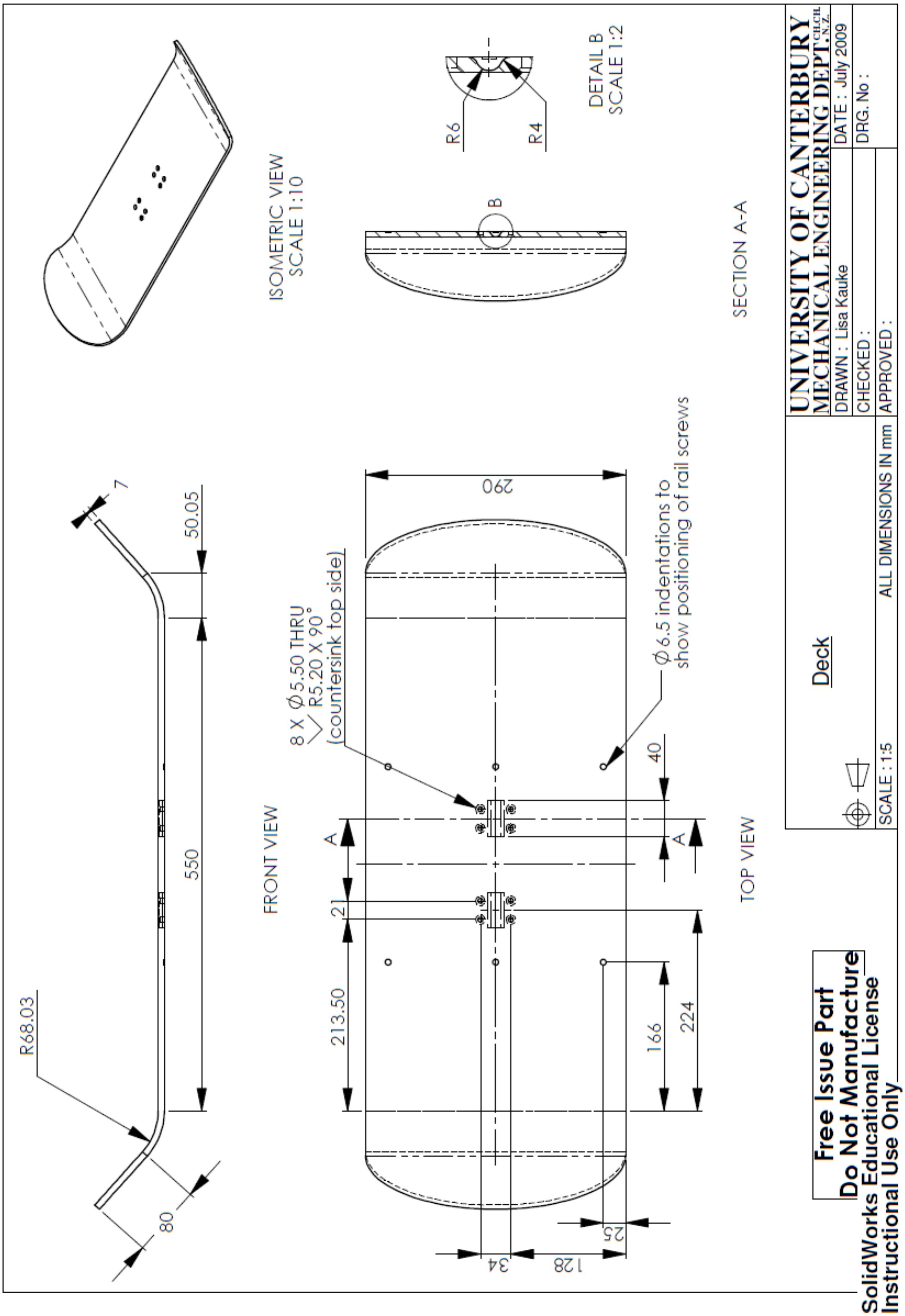
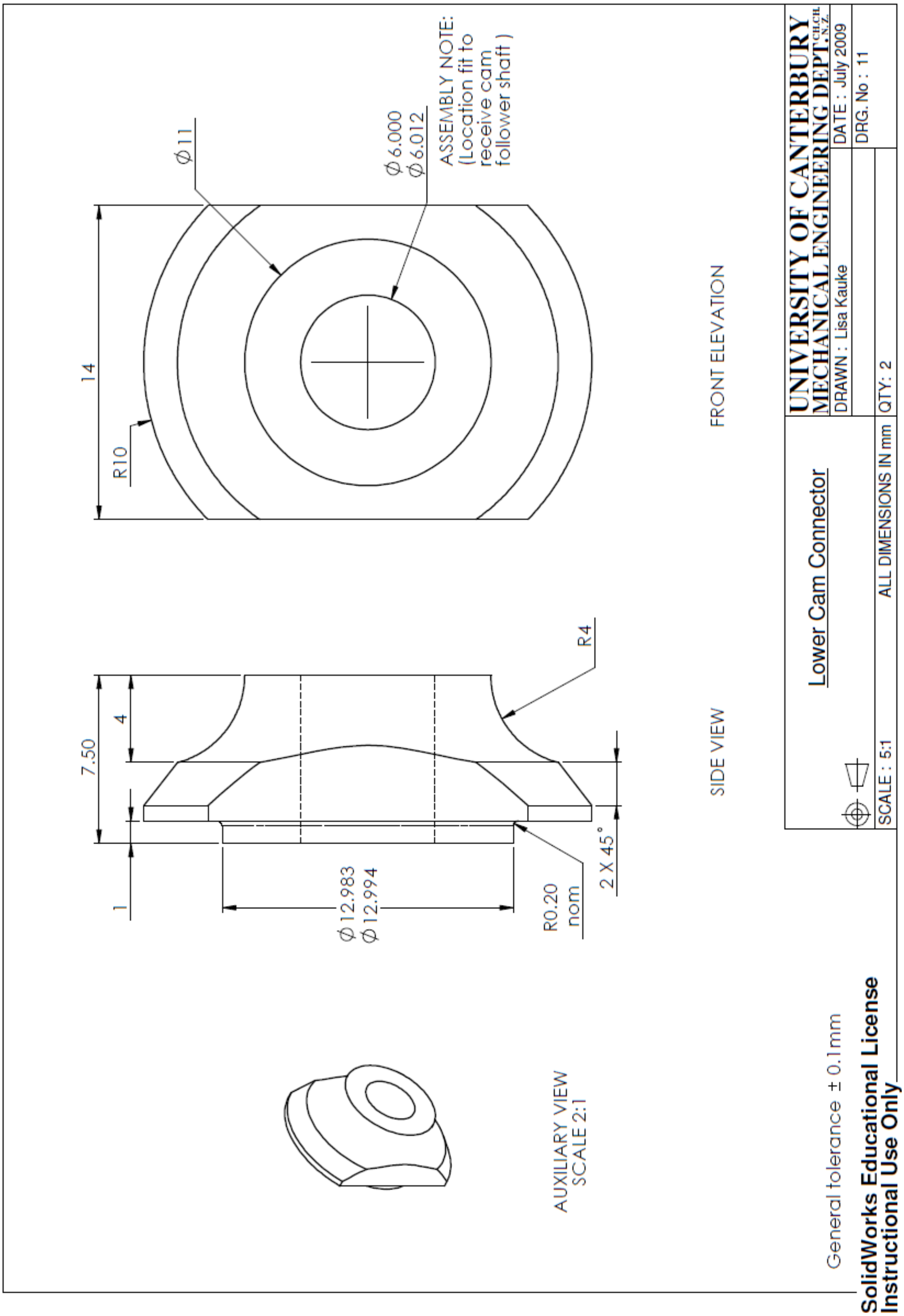
Instructional Use Only


ISOMETRIC VIEW
SCALE 1:10
R6
R4
DETAIL B
SCALE 1:2
B
SECTION A-A
R68.03
7
50.05
550
80
FRONT VIEW
290
8 X Ø 5.50 THRU
R5.20 X 90°
(countersink top side)
Ø 6.5 indentations to
show positioning of rail screws
40
A
A
21
213.50
166
224
25
34
128
TOP VIEW
UNIVERSITY OF CANTERBURY
MECHANICAL ENGINEERING DEPT. CH.CH. N.Z.
DRAWN : Lisa Kauke
DATE : July 2009
CHECKED :
DRG. No :
APPROVED :
ALL DIMENSIONS IN mm
Deck
SCALE : 1:5
Free Issue Part
Do Not Manufacture
SolidWorks Educational License
Instructional Use Only


ASSEMBLY NOTE:
(Location fit to
receive cam
follower shaft)
Ø11
Ø6.000
Ø6.012
14
R10
FRONT ELEVATION
7.50
4
R4
1
Ø12.983
Ø12.994
R0.20
nom
2 X 45°
SIDE VIEW
AUXILIARY VIEW
SCALE 2:1
General tolerance ± 0.1mm
UNIVERSITY OF CANTERBURY CH.CH. N.Z.
MECHANICAL ENGINEERING DEPT.
DRAWN : Lisa Kauke
DATE : July 2009
DRG. No : 11
Lower Cam Connector
SCALE : 5:1
ALL DIMENSIONS IN mm
QTY: 2
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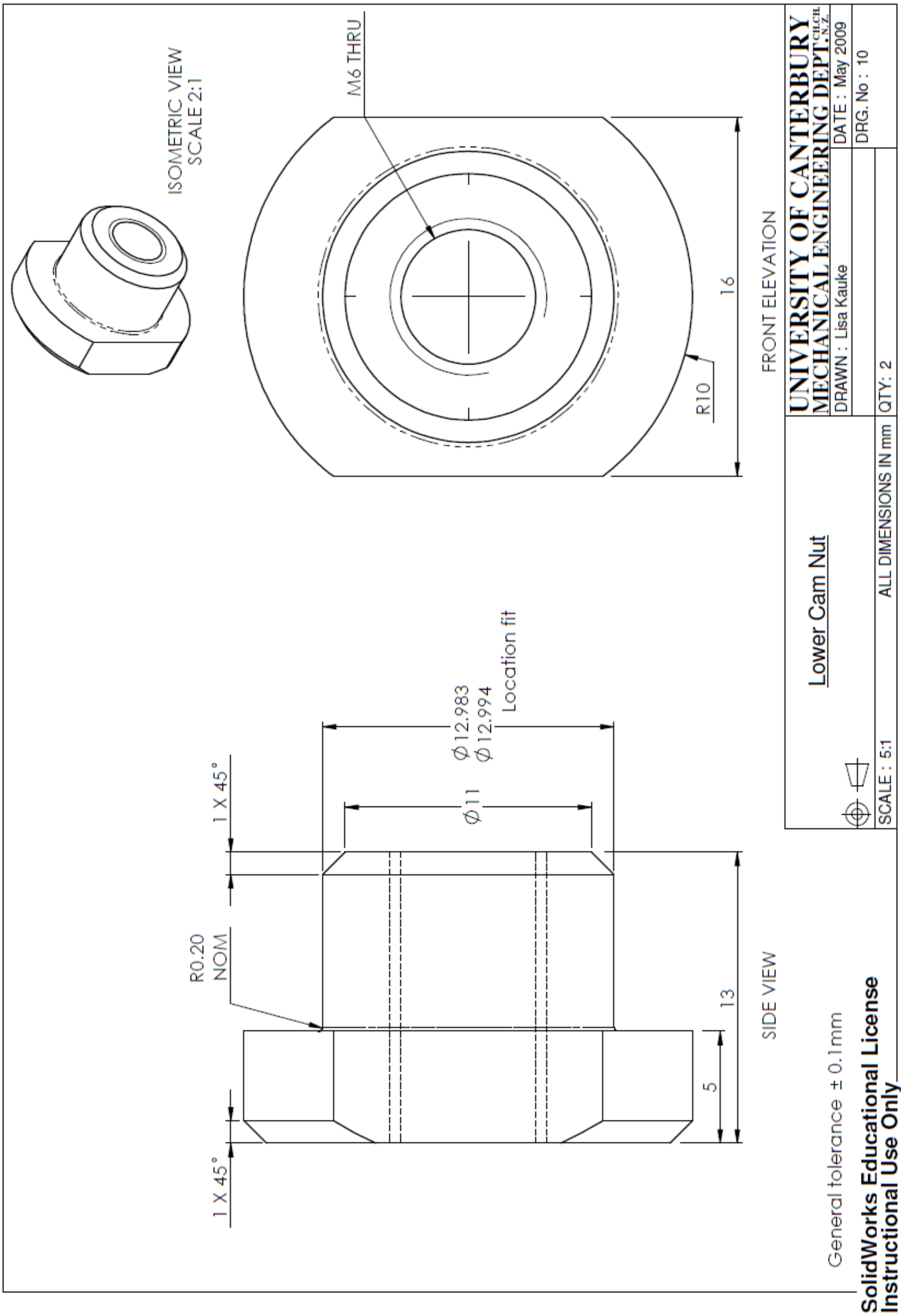
Instructional Use Only


ISOMETRIC VIEW
SCALE 2:1
M6 THRU
16
R10
FRONT ELEVATION
1 X 45°
R0.20
NOM
Ø11
Ø12.983
Ø12.994
Location fit
13
5
1 X 45°
SIDE VIEW
General tolerance ± 0.1mm
UNIVERSITY OF CANTERBURY CH.CH.
MECHANICAL ENGINEERING DEPT. N.Z.
DRAWN : Lisa Kauke
DATE : May 2009
DRG. No : 10
Lower Cam Nut
SCALE : 5:1
ALL DIMENSIONS IN mm
QTY: 2
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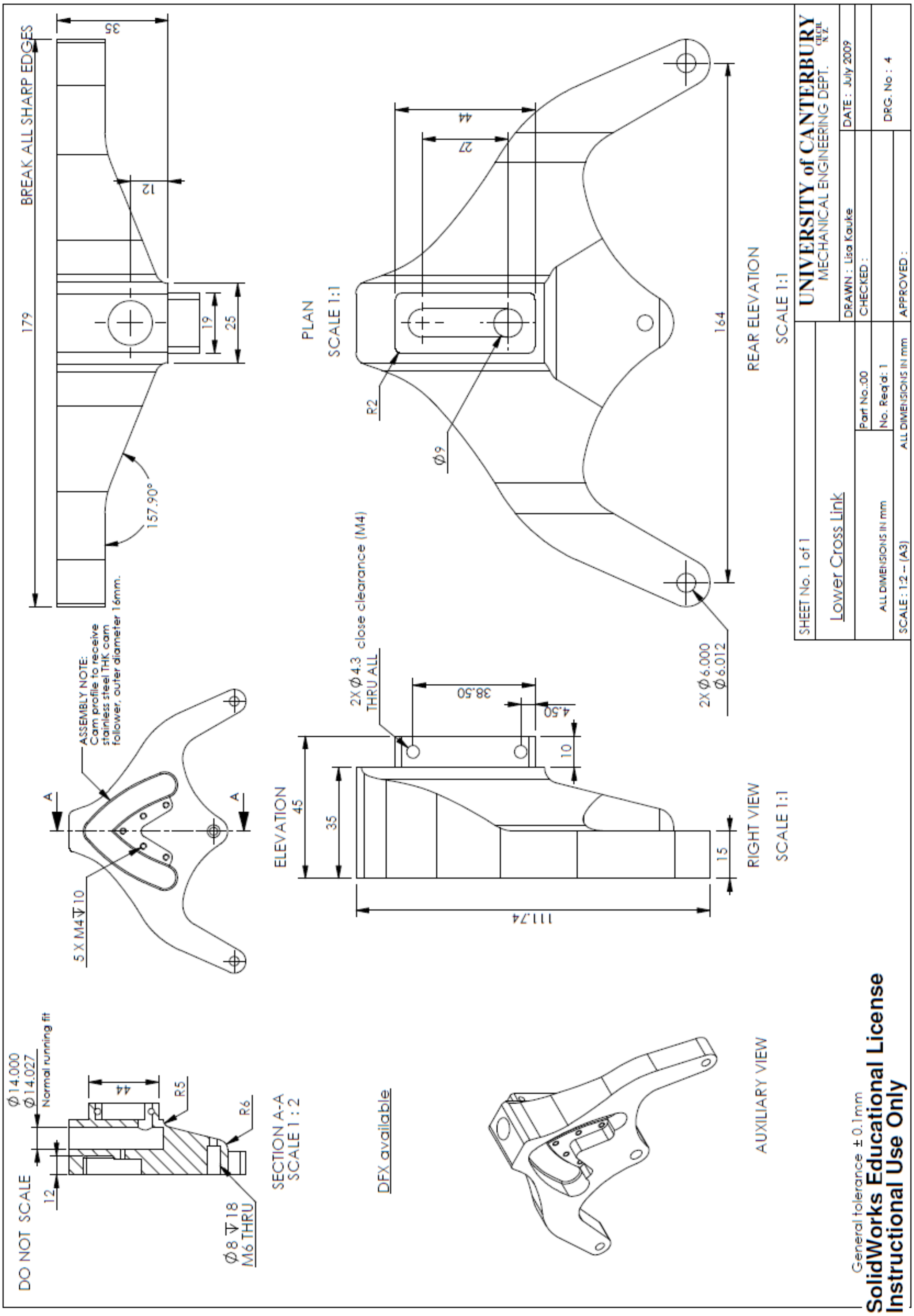
DO NOT SCALE
BREAK ALL SHARP EDGES
179
35
12
19
25
157.90°
PLAN
SCALE 1:1
44
27
R2
Ø9
164
2X Ø6.000
Ø6.012
REAR ELEVATION
SCALE 1:1
ASSEMBLY NOTE:
Cam profile to receive
stainless steel THK cam
follower, outer diameter 16mm.
A
A
5 X M4 ↧10
2X Ø4.3 close clearance (M4)
THRU ALL
38.50
4.50
10
ELEVATION
45
35
15
111.74
RIGHT VIEW
SCALE 1:1
Ø14.000
Ø14.027
Normal running fit
44
R5
R6
12
Ø8 ↧18
M6 THRU
SECTION A-A
SCALE 1 : 2
DFX available
AUXILIARY VIEW
General tolerance ± 0.1mm
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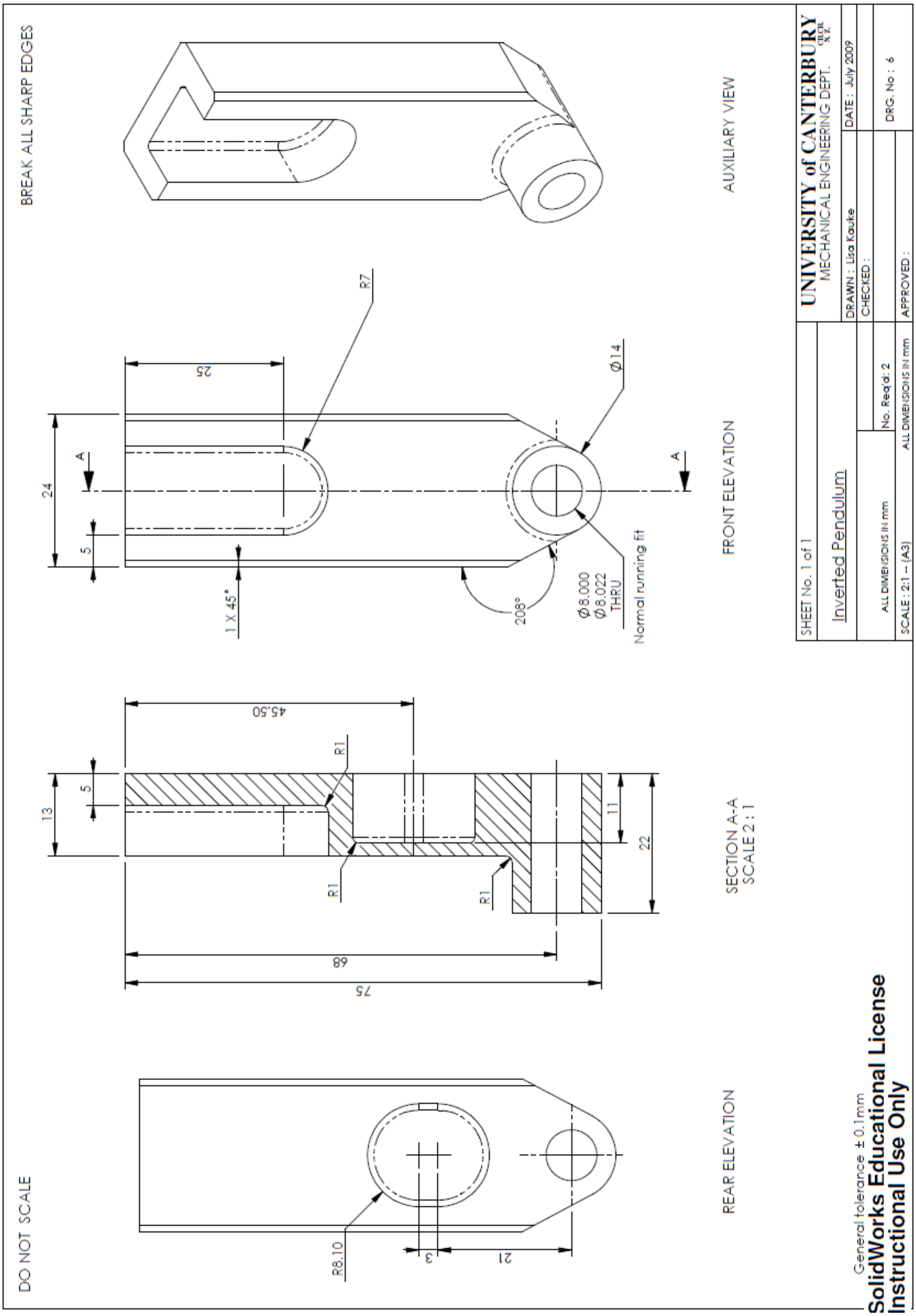
CHCH. N.Z.
MECHANICAL ENGINEERING DEPT.
SHEET No. 1 of 1
Lower Cross Link
DRAWN : Lisa Kauke
CHECKED :
DATE : July 2009
Part No.:00
No. Req'd.: 1
ALL DIMENSIONS IN mm
SCALE : 1:2 -- (A3)
APPROVED :
DRG. No : 4


DO NOT SCALE
BREAK ALL SHARP EDGES
AUXILIARY VIEW
FRONT ELEVATION
SECTION A-A
SCALE 2 : 1
REAR ELEVATION
A
A
25
24
5
R7
Ø14
1 X 45°
208°
Ø8.000
Ø8.022
THRU
Normal running fit
45.50
13
5
R1
R1
R1
11
22
68
75
R8.10
3
21
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MECHANICAL ENGINEERING DEPT.
DRAWN : Lisa Kauke
CHECKED :
APPROVED :
DATE : July 2009
DRG. No : 6
SHEET No. 1 of 1
Inverted Pendulum
ALL DIMENSIONS IN mm
No. Req'd: 2
SCALE : 2:1 – (A3)
ALL DIMENSIONS IN mm
General tolerance ± 0.1mm
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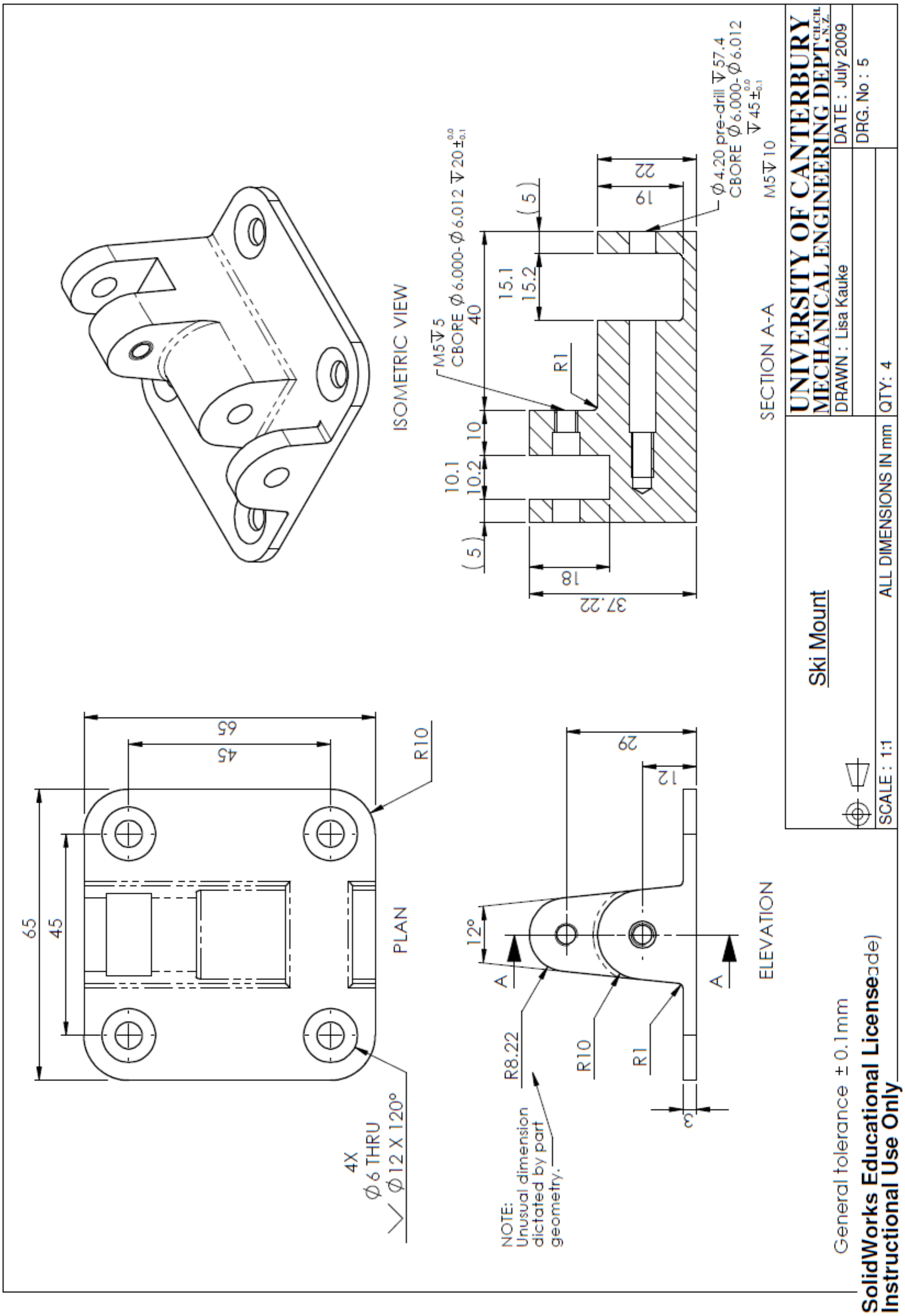
ISOMETRIC VIEW
SECTION A-A
M5 ↧ 5
CBORE Ø 6.000-Ø 6.012 ↧ 20
Ø 4.20 pre-drill ↧ 57.4
CBORE Ø 6.000-Ø 6.012
↧ 45
M5 ↧ 10
40
(5)
15.1
15.2
19
22
R1
10
10.1
10.2
(5)
18
37.22
PLAN
65
45
65
45
R10
4X
Ø 6 THRU
Ø 12 X 120°
ELEVATION
12°
A
A
29
12
R8.22
R10
R1
3
NOTE:
Unusual dimension
dictated by part
geometry.
General tolerance ± 0.1mm
UNIVERSITY OF CANTERBURY CH.CH. N.Z.
MECHANICAL ENGINEERING DEPT.
DRAWN : Lisa Kauke
DATE : July 2009
DRG. No : 5
QTY: 4
Ski Mount
SCALE : 1:1
ALL DIMENSIONS IN mm
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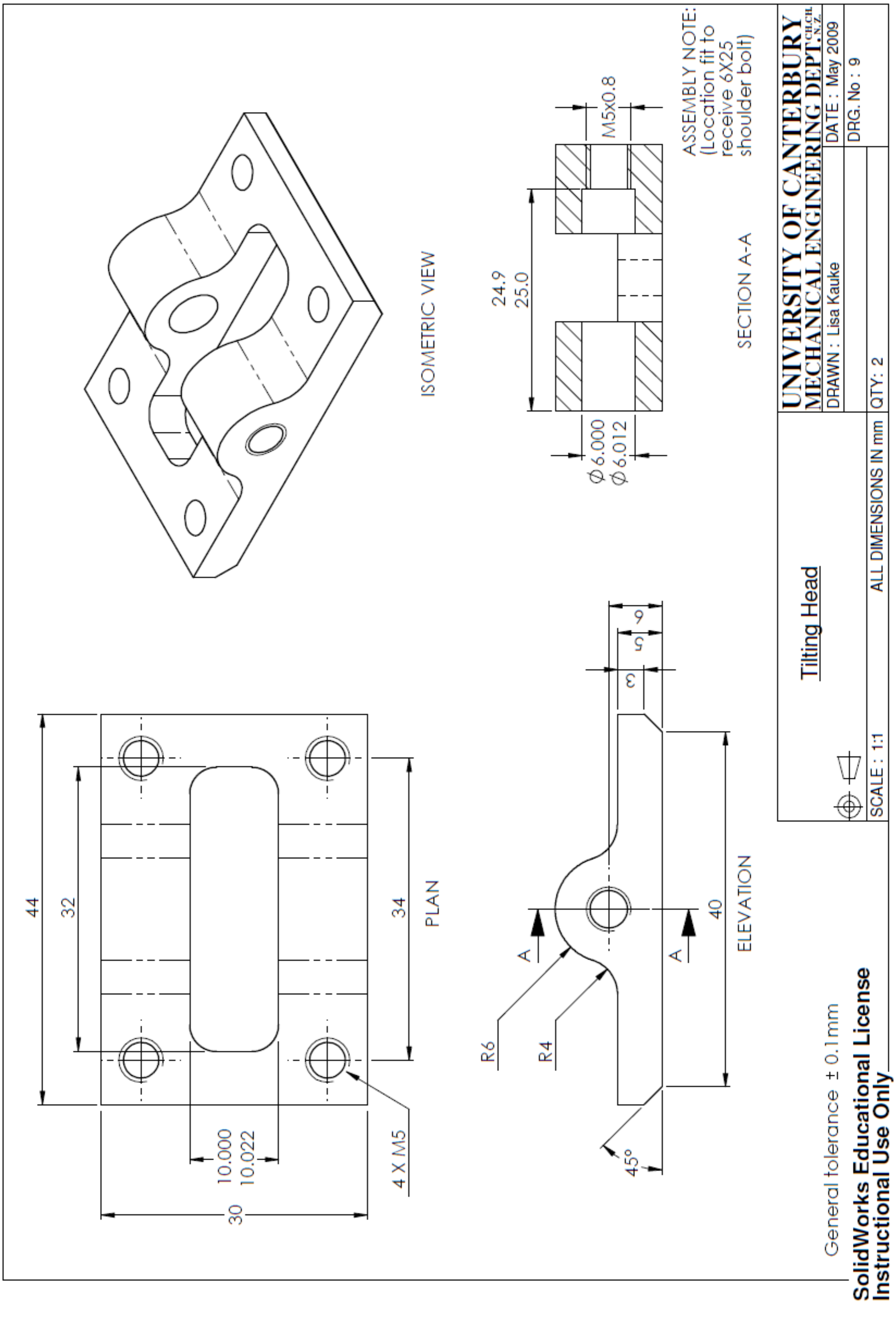
Instructional Use Only


PLAN
44
32
34
30
10.000
10.022
4 X M5
ELEVATION
R6
R4
A
A
40
45°
3
5
6
ISOMETRIC VIEW
SECTION A-A
24.9
25.0
Ø 6.000
Ø 6.012
M5x0.8
ASSEMBLY NOTE:
(Location fit to
receive 6X25
shoulder bolt)
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MECHANICAL ENGINEERING DEPT.
DRAWN : Lisa Kauke
DATE : May 2009
DRG. No : 9
QTY: 2
Tilting Head
ALL DIMENSIONS IN mm
SCALE : 1:1
General tolerance ± 0.1mm
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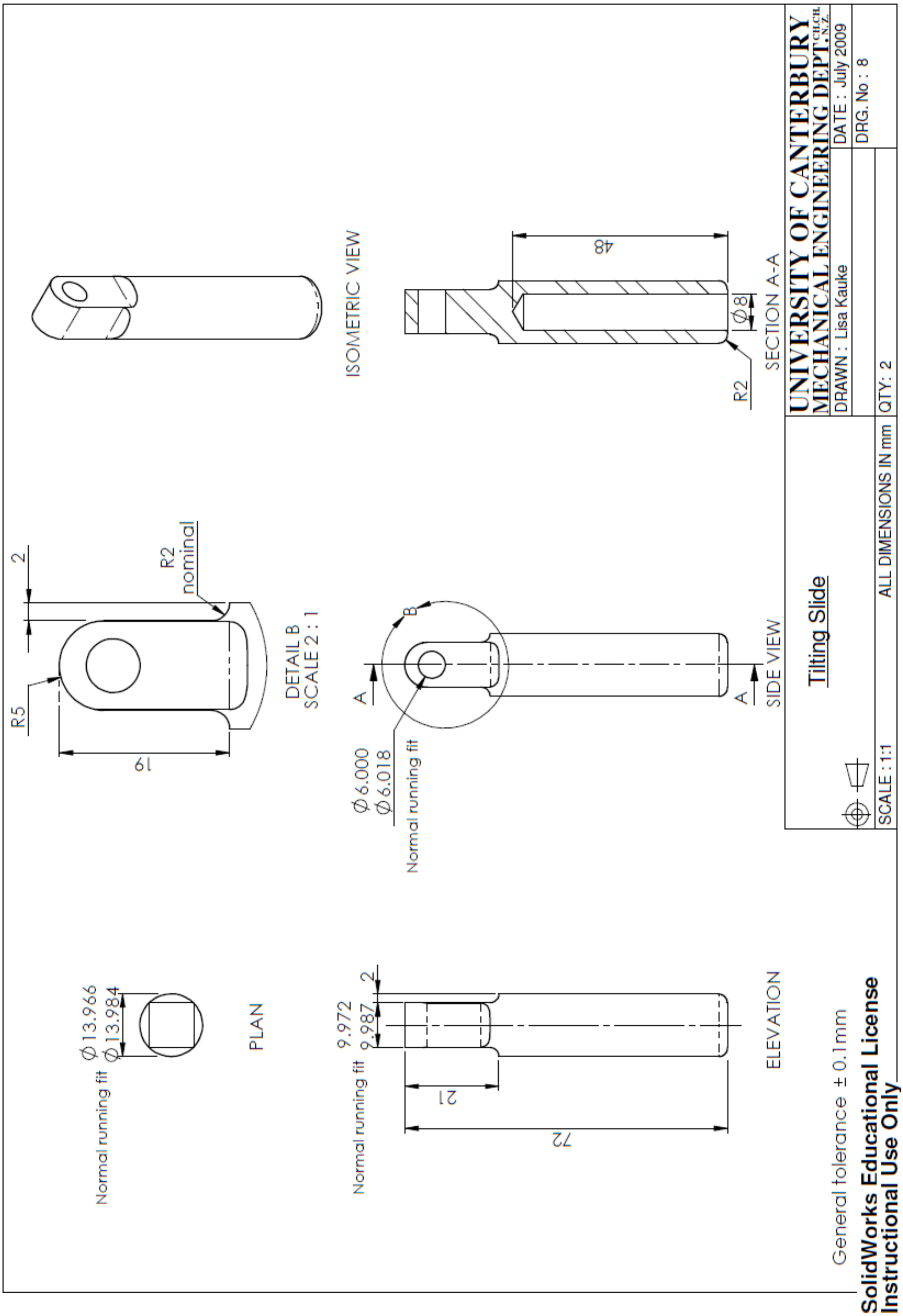
ISOMETRIC VIEW
48
Ø8
R2
SECTION A-A
2
R2
nominal
R5
19
DETAIL B
SCALE 2 : 1
A
A
B
Ø6.000
Ø6.018
Normal running fit
SIDE VIEW
Normal running fit
Ø13.966
Ø13.984
PLAN
Normal running fit
9.972
9.987
2
21
72
ELEVATION
General tolerance ± 0.1mm
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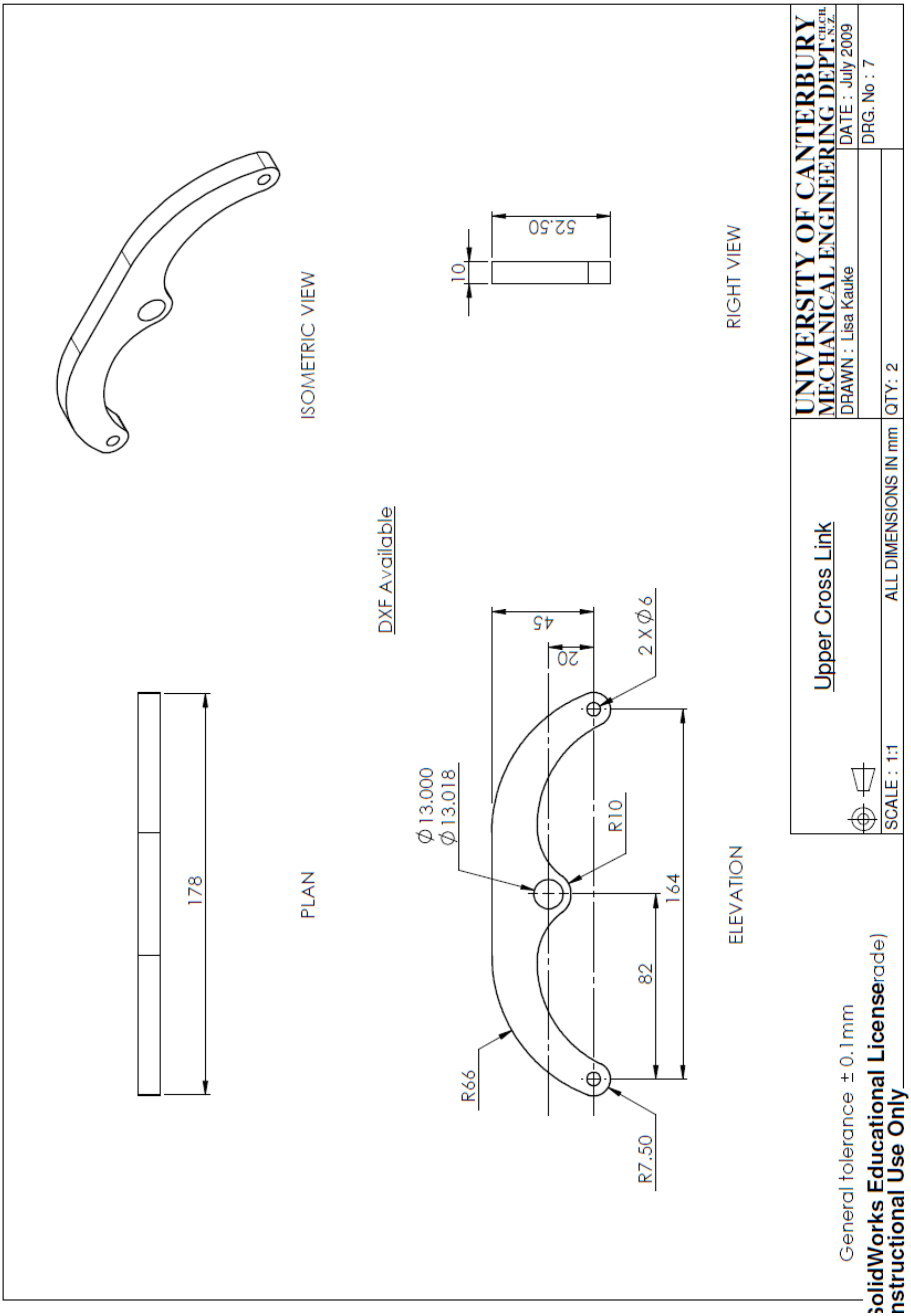
MECHANICAL ENGINEERING DEPT. CH.CH. N.Z.
DRAWN : Lisa Kauke
DATE : July 2009
DRG. No : 8
Tilting Slide
ALL DIMENSIONS IN mm
QTY: 2
SCALE : 1:1



ISOMETRIC VIEW
RIGHT VIEW
10
52.50
PLAN
178
ELEVATION
DXF Available
45
20
2 X Ø6
Ø13.000
Ø13.018
R10
164
82
R66
R7.50
General tolerance ± 0.1mm
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Upper Cross Link
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MECHANICAL ENGINEERING DEPT. CH.CH N.Z.
DRAWN : Lisa Kauke
DATE : July 2009
DRG. No : 7
QTY: 2
ALL DIMENSIONS IN mm
SCALE : 1:1

References

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